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PLASMA OSCILLATIONS IN A LOW PRESSURE ARGON DISCHARGE

JOHN A. FLYNN
and
EUGENE E. SHOULTS

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John A. Flynn

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Eugene E. Shoults

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by

John A. Flynn

Lieutenant, United States Coast Guard

and

Eugene E. Shoults

Captain, United States Marine Corps

Submitted in partial fulfillment of
the requirements for the degree of

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IN
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~~Thesis~~

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ABSTRACT

A continuation of the work initiated by LCDR. Howard T. Webb and Lt. Alan S. Garner in the field of plasma oscillations in low pressure argon at the United States Naval Postgraduate School is presented. Verification of data compiled by Webb and Garner and an extension of the range of pressures and tube geometries was made using the equipment described in their thesis on this subject.

Included is a brief resume of previous work in the field of gaseous discharges together with recommendations for further work and modifications of the equipment.

The assistance of Professor N. L. Oleson of the United States Naval Postgraduate School in this undertaking, and his continued support and counsel is gratefully acknowledged.

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1. Introduction.

Recent developments in controlled fusion reactions, low frequency noise investigations, and allied investigations indicate the need for further fundamental research in the field of electrical discharges especially with the oscillation phenomena observed at low pressures in various inert gases. This report covers plasma oscillations observed in argon gas discharges at low pressures.

Plasma as used in this paper will mean ionized regions in gas discharges where the concentration of positive and negative ions are approximately equal so that for a large volume the overall electric charge is essentially neutral.[1] Two such examples of plasma are positive columns of the glow and arc discharges which exhibit high conductivity and consequently a relatively low voltage gradient. In rare gas plasmas the electrons are the negative carriers of the current, since in these cases they do not attach themselves to atoms to form negative ions in which case these ions are the negative carriers, i. e. in oxygen or chlorine. The electrons, the positive ions and the neutral molecules may be in thermal equilibrium (in which case the kinetic energies are equal), but in general they are not; since the plasma is established by an electric field the electron temperature greatly exceeds the positive ion temperature which in turn exceeds the gas temperature.

In the plasma a maxwellian distribution may be assumed for the

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[1] J. D. Cobine, Gaseous Conductors, pp. 130, McGraw-Hill Book Co., Inc. 1941

velocities of both the ions and the electrons although Langmuir, Compton, and others have observed deviations from this distribution.[2] Although the applied electric field increases the ion and electron temperatures, it does not necessarily produce a departure from the maxwellian distribution, since the drift current density is usually much smaller than the random current density of the ions and electrons. The applied field increases the energies of the electrons to values much greater than those of positive ions, for the electrons have a greater acceleration due to their smaller mass. The electrons lose little of their energy by elastic scattering to the neutral gas molecules because of their small mass ratio and hence do not significantly raise the gas temperature. Since the positive ions have nearly the same mass as the neutral molecules, the ions can increase the gas temperature by elastic collisions.

Although a macroscopic volume of plasma must by essentially neutral, portions of the plasma may have high electric fields due to variations with time in surrounding charge concentrations. The ionizations in a plasma are maintained primarily by electron collisions, although some photo-ionization also contributes. Electrons which are accelerated through the electric field in the cathode fall space gain a considerable amount of energy and are referred to as primary electrons.

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[2] K. T. Compton and I. Langmuir, Rev. Mod. Phys.,2, pp. 227, April 1930

Plasma oscillation experiments are generally conducted in gas filled diodes or triodes (the latter being the instrument used for the present investigation). The glow discharges usually employ mercury, argon, or similar gases. The voltage variation across the tube consists of a steep rise from the cathode to the beginning of the negative glow, a slow rise in potential across the remaining length of the tube except for a small sharp rise to the anode.[3] Thus the major voltage rise experienced by electrons traversing the inter-electrode distance occurs close to the cathode. This sharp rise in voltage is called, incongruously, the "cathode fall". Since electron mobilities are greater than those for positive ions, the cathode is surrounded by a positive ion sheath. The portion of the discharge, from cathode through the Faraday dark space, remains fixed in size as the inter-electrode distance is varied, so that frequently for oscillation experiments with small inter-electrode distances, the positive column is not observed and the discharge appears to terminate at the negative glow. Except for that region very near the cathode, the concentrations of positive ions and electrons are approximately equal, and this constitutes the plasma.[4]

Two types of stable longitudinal oscillations may be considered possible in a plasma of a gaseous discharge. Due to local perturbation of electron-positive ion densities with later modulation of the passing fast primary electrons, probably by a feedback or growing wave mechanism, a group of electrons may oscillate at high frequency while the positive ions remain relatively fixed in position. The

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[3] Cobine, op. cit., pp. 132

[4] A. Von Engel, Ionized Gases, pp. 243 Oxford University Press, 1955

positive ions may also oscillate, but because of their large mass the oscillation frequency will be much lower than the electron oscillation frequency.

2. Previous Work

While making investigations of scattering of electrons in low pressure mercury discharges, in 1924 Langmuir and Mott-Smith[5] found that some of the electrons emitted by the cathode acquired energies greater than the potential across the tube. This type of discharge has a large voltage rise across the cathode space charge sheath, and since the remainder of the tube containing the plasma is approximately at anode potential, the fast or primary electrons extending beyond the cathode sheath would be expected to have energies approximating the tube potential. Others of the primary electrons were determined to have less energy than expected, indicating that energy "scattering" had occured, even though the mean energy was little changed. The explanation suggested for this effect was that oscillations, not detected, were occuring in the discharge tube.

Dittmer[6], while studying the variation in scattering with tube voltage and current, gas pressure, and with distance from the cathode, found the region of scattering approaches the cathode as the discharge current is increased. Dittmer concluded that there might well be a fluctuating potential in the discharge and pointed out that a

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[5] I. Langmuir and H. Mott-Smith, Gen. Elec. Rev., pp. 449, 538, 666 762, 810, August-November, 1924

[6] A. F. Dittmer, Phys. Rev., 28, pp. 507, September, 1926

small change in the electron density distribution could cause considerable potential change. Dittmer hypothesized the existance of plasma oscillations to explain the fluctuation in potential but was unable to detect these oscillations experimently, possibly due to inadequate high frequency detection equipment.

Penning[7], by using a Lecher wire circuit, discovered oscillations with frequencies from 300 to 600 megacycles and observed that electron scattering was accompanied by oscillations.

Langmuir and Tonks[8] extended the range of oscillation detection from 1-1000 megacycles observing that oscillations occurred generally throughout the range but with sharp peaks depending on the impressed electric field. They postulated that the low energy (plasma) electrons vibrated at frequencies dependent on their concentration while the massive positive ions could be likened to a jelly of positive charge and uniform density. The displacement, S, of a group of electrons in a small region of plasma would cause an unbalanced force proportional to the magnitude of the displacement and the amount of charge. This restoring force, E, would then cause oscillations about the equilibrium positions at a frequency of $f^2 = \frac{Ne^2}{\pi m}$ or $f = 8980 N^{1/2}$. Langmuir and Tonks verified the above relationship thus demonstrating that there was no symmetry dependence for these oscillations. Further, the absence of space coordinates in the equation showed that the oscillations did not propagate throughout the plasma.

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[7] F. M. Penning, Nature, 118, pp. 301, 1926

[8] L. Tonks and I. Langmuir, Phys. Rev., 38, pp. 1219, 1931

Druyvesteyn and Warmoltz[9], in their studies of arc discharges with a hot cathode, in 1937 noticed that changes in velocity distribution, space potential and charge density occurred in distinct narrow regions, and postulated the existance of micro-fields in the plasma to explain the effects.

In 1939, Merrill and Webb[10] investigated the relationship between the plasma oscillations and the scattering of the primary beam in mercury arc discharges. They determined electron temperature and concentration using the method of Langmuir and Mott-Smith[11], the electron velocity distribution using an analysis of tube voltage-current characteristics, and the intensity and position of plasma oscillations and electron scattering by measurements with a tungsten probe which could be moved in small steps to any part of the discharge. They confirmed the data of Druyvesteyn and Warmoltz, that velocity modulation and bunching of the fast electrons occurred in narrow regions. Since the oscillations of definite frequencies were observed in arc discharge only where fast electrons were undergoing scattering, Merrill and Webb concluded that these electrons supply the energy for the oscillation of the plasma (ultimate) electrons. Excellent agreement was obtained between measured frequencies of oscillations and those computed by use of Langmuir and Tonks electron density formula.

[10] H. J. Merrill and H. W. Webb, Phys. Rev., 55, pp. 1191, June, 1939

[11] I. Langmuir and H. Mott-Smith, Gen. Elec. Rev., Vol.27, Nos. 7, 8, 9, 11, 12, 1924

Armstrong, Emeleus, and Neill[12] continued the investigations of Merrill and Webb, and concluded that the oscillations are stable and reproducible, varying in frequency and magnitude over the tube characteristics. The oscillation frequency varied directly with gas pressure, was independent of probe bias, and agreed with the Langmuir-Tonks formula.

In 1953, Looney and Brown[13] utilized a new technique to excite plasma oscillations. A beam of high energy electrons, injected into the plasma of a D. C. discharge, excited oscillations in the plasma at the frequency given by the Langmuir-Tonks formula. The existance of standing-wave patterns of the oscillatory energy in the region of the plasma in and around the electron beam were shown by a movable probe. The standing-wave patterns were independent of the frequency of the oscillation and were determined by the thickness of the ion sheaths on the bounding electrodes. By the detailed behavior of the frequency of oscillation and the transitions in the standing-wave patterns as the sheath thickness was varied, the mechanism of the energy transfer from the electron beam to the oscillation of the plasma electrons was established as a velocity modulation process. They also proposed that the oscillations were a type of longitudinal pressure wave set up in the plasma electrons.

T. K. Allen[14] has shown the reliability of probe analysis in

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[12] E. B. Armstrong and K. G. Emeleus, Proc. Inst. E. E. (London), 96, pt. III, No. 43, pp. 390, September, 1949

[13] D. H. Looney and S. C. Brown, Phys. Rev., 93, pp. 965, March, 1954

[14] T. K. Allen, Ph. D. Thesis, Queens Univ. of Belfast, 1954

investigating electron energy scattering. Abrupt appearances of this energy scattering at a particular distance from the cathode was found to be independent of the presence of the probe.

The variation of oscillation intensity with distance from the cathode was examined for a wide range of conditions and analysed in terms of wave feedback from the detecting probe. The peaks observed were shown by Allen to represent feedback in phase from probe to cathode, each peak representing an integral number of beam wavelengths between probe and cathode.

He demonstrated further that the traveling wave group velocity between probe and cathode is constant along the primary beam and that this velocity is very near that of an extra group of electrons near the meniscus which have energies approximately equal to the anode potential. (The term meniscus as used here refers to a lens-shaped region, brighter than the surrounding plasma, which begins near the cathode and terminates in a dark layer a few millimeters from the cathode.)

Several workers have investigated radio frequency noise in hot-cathode discharges and have suggested that coronal plasma oscillations are responsible for certain forms of solar radio noise. In 1951, Martin and Woods[15] conducted a systematic investigation of low-frequency electrical noise and found that low-frequency electrical noise with a broad continous spectrum extending from audio frequencies into at least the megacycle region is generated by a variety of low-

[15] H. Martin and H. A. Woods, Proc, of the Phys. Soc., B, Vol.LXV, 1952

pressure tubes. Their evidence indicated that much of the noise originates at the cathode, or close to it, and that it is due to pulse-like fluctuations in the electron current leaving the cathode region. They also found that the noise was dependent on the operating point of the current-voltage characteristic curve of the tube. Thong Saw Pak[16] in 1954 found that radio noise is closely connected with the fluctuation of space-charge sheaths and found the noise level to be much higher throughout the non-saturated part of the characteristic curve, dropping to a low level with current saturation. Thong Saw Pak's results closely confirmed the work of Martin and Woods. In 1954 Steele[17] investigated the physical processes in the fluorescent lamp which cause radio noise. He found that radiated noise is caused by four different types of oscillations, the most important of which (in the broadcast band) occurs near the cathode and extends to frequencies greater than ten megacycles.

3. Equipment and Techniques

The equipment consisted of four main components as follows:

(1) Gaseous discharge tube, in which oscillations were produced.

(2) D. C. circuits for the control of the discharge conditions.

(3) Oscillation detection and measuring equipment.

(4) Vacuum system for the evacuation and filling of the tube.

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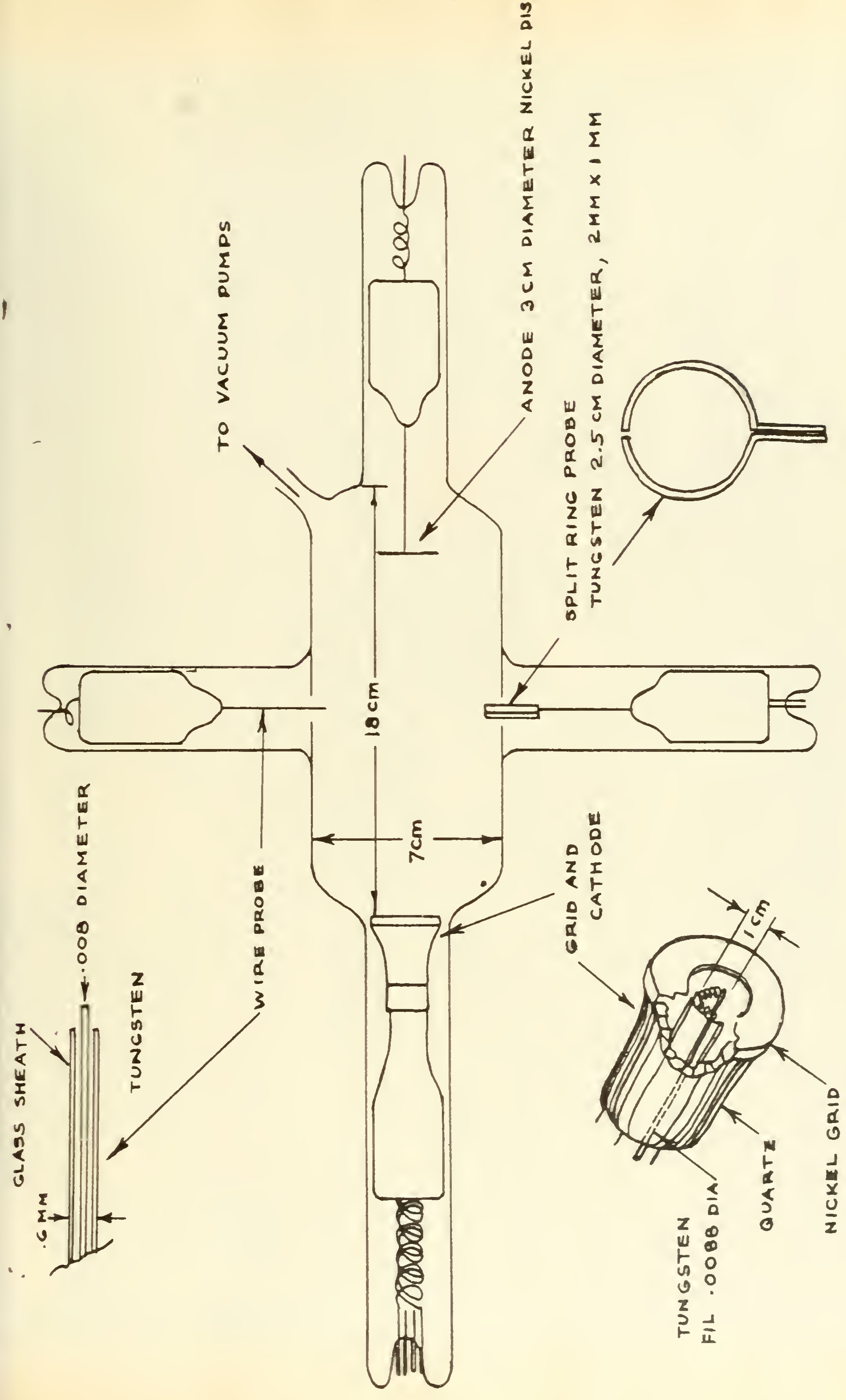
[16] Thong Saw Pak, Proc. of the Phys. Soc., B, Vol. LXVIII, 1955

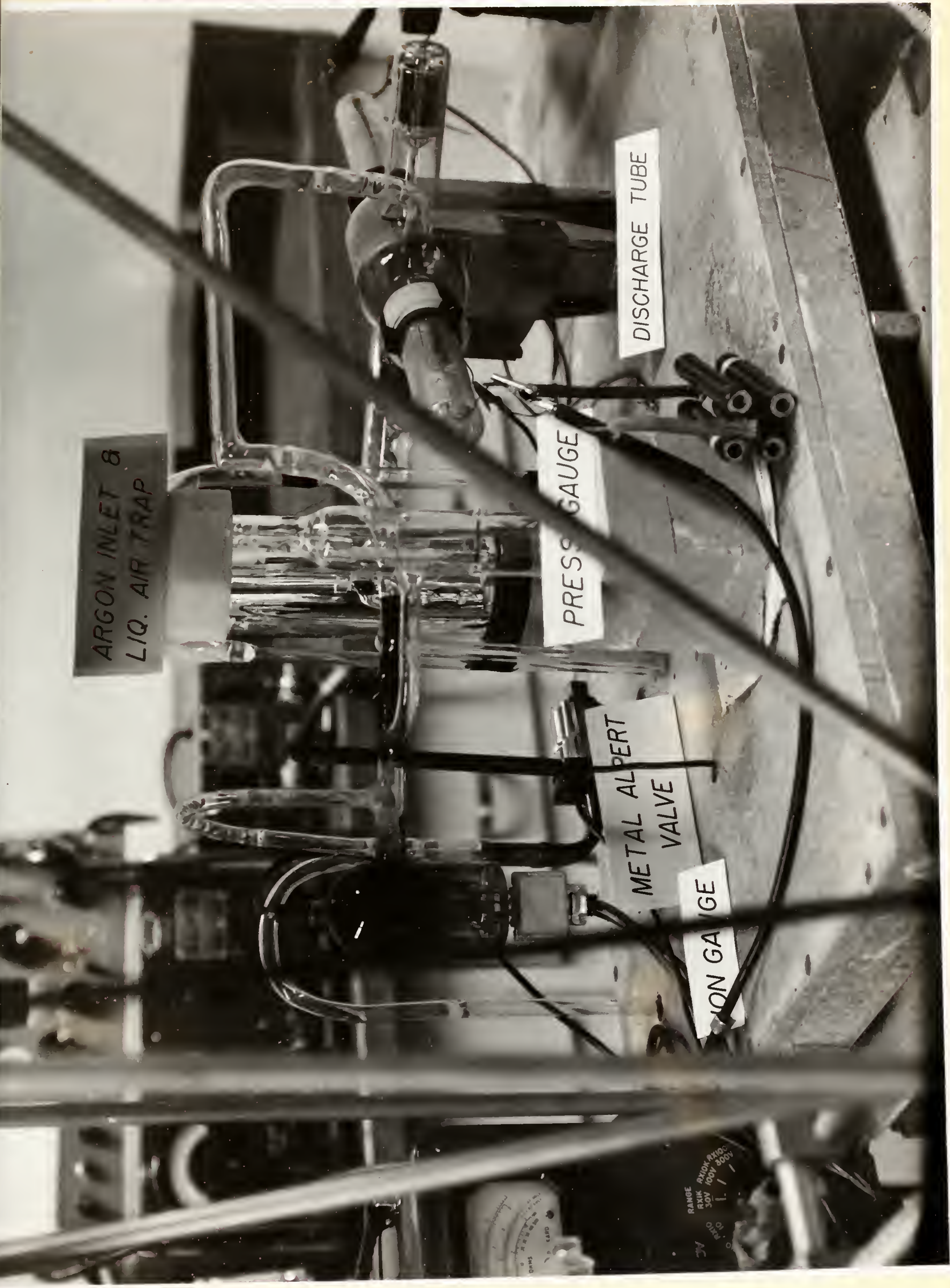
[17] H. L. Steele, Jr., Illuminating Engineering, Vol. XLIX, No. 7, July 1954

FIG. 1.



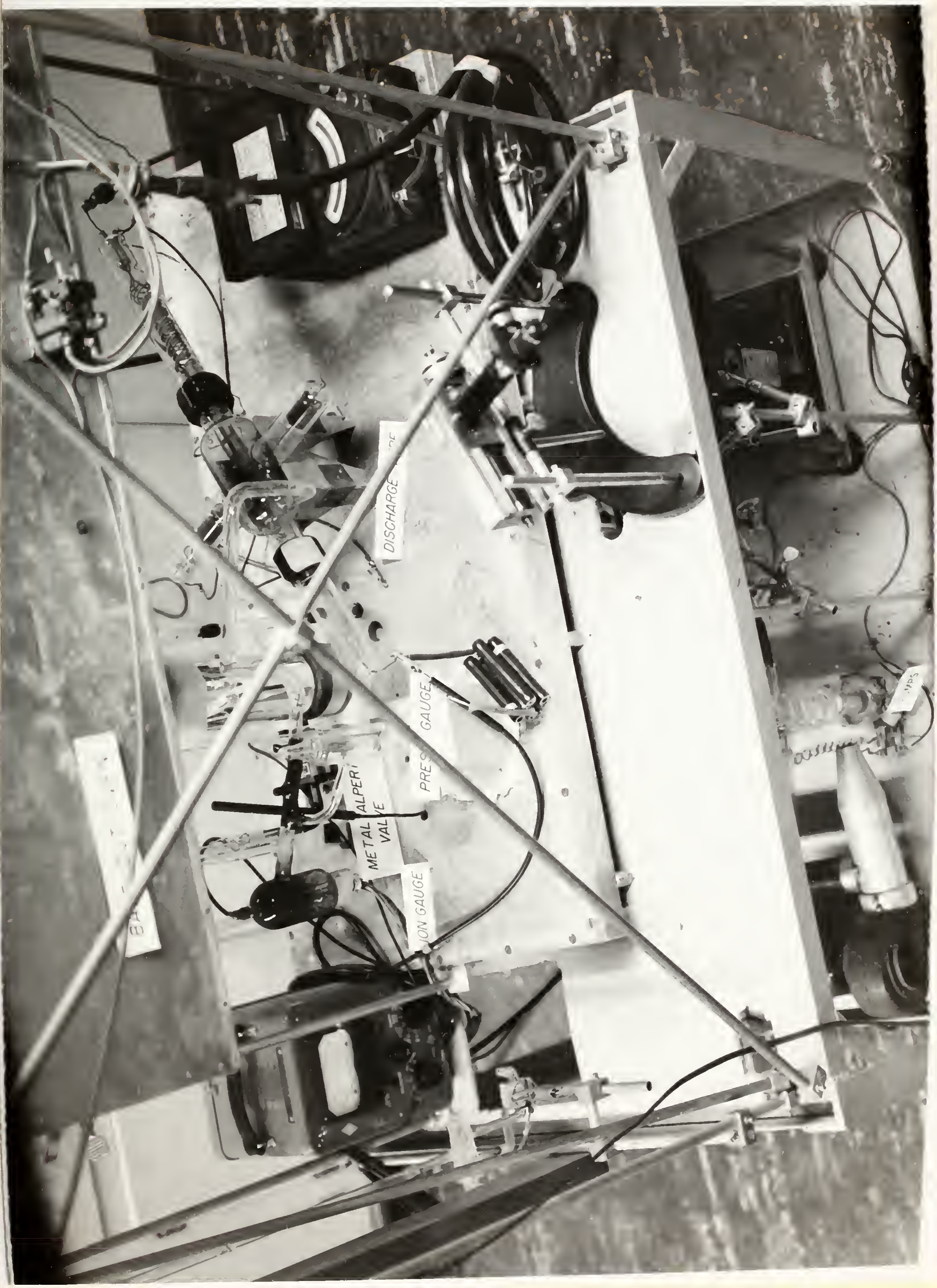
PLASMA OSCILLATION TUBE

Fig. 2



SIDE VIEW OF OSCILLATION TUBE

Fig. 3



TOP VIEW OF OSCILLATION TUBE

Webb and Garner[18] designed and assembled the experimental system, and the present workers made only minor modifications to the system.

a. Discharge Tube. Fig. 1 is a detailed drawing of the tube used in this work. It was constructed at Stanford Research Institute, Palo Alto, California. The tube was constructed so that it would be flexible enough to verify previous data in the field in addition to investigating new characteristics of plasma oscillations. Design recommendations of previous workers in the field were utilized in the construction of the tube.

The cathode was designed along conventional lines. It consisted of two coiled tungsten filaments which could be operated seperately or in series, with a voltage drop of approximately nine volts across each element. Enclosing the filaments was a quartz cylinder with a nickel ring around the emission end which could be employed as a grid. Allen's[19] recommendation that a large disc electrode be used for the plate was adopted.

A standard wire probe and a split ring probe were used to probe the plasma. The tungsten wire probe was patterned after a design recommended by Wehner and Medicus.[20] The split ring probe was an attempt to satisfy the requirement of detecting oscillations with the minimum disturbance to the field while also being capable of distinguishing between different lateral modes of oscillation. The ring probe could be rotated so that the plane of the ring could be placed

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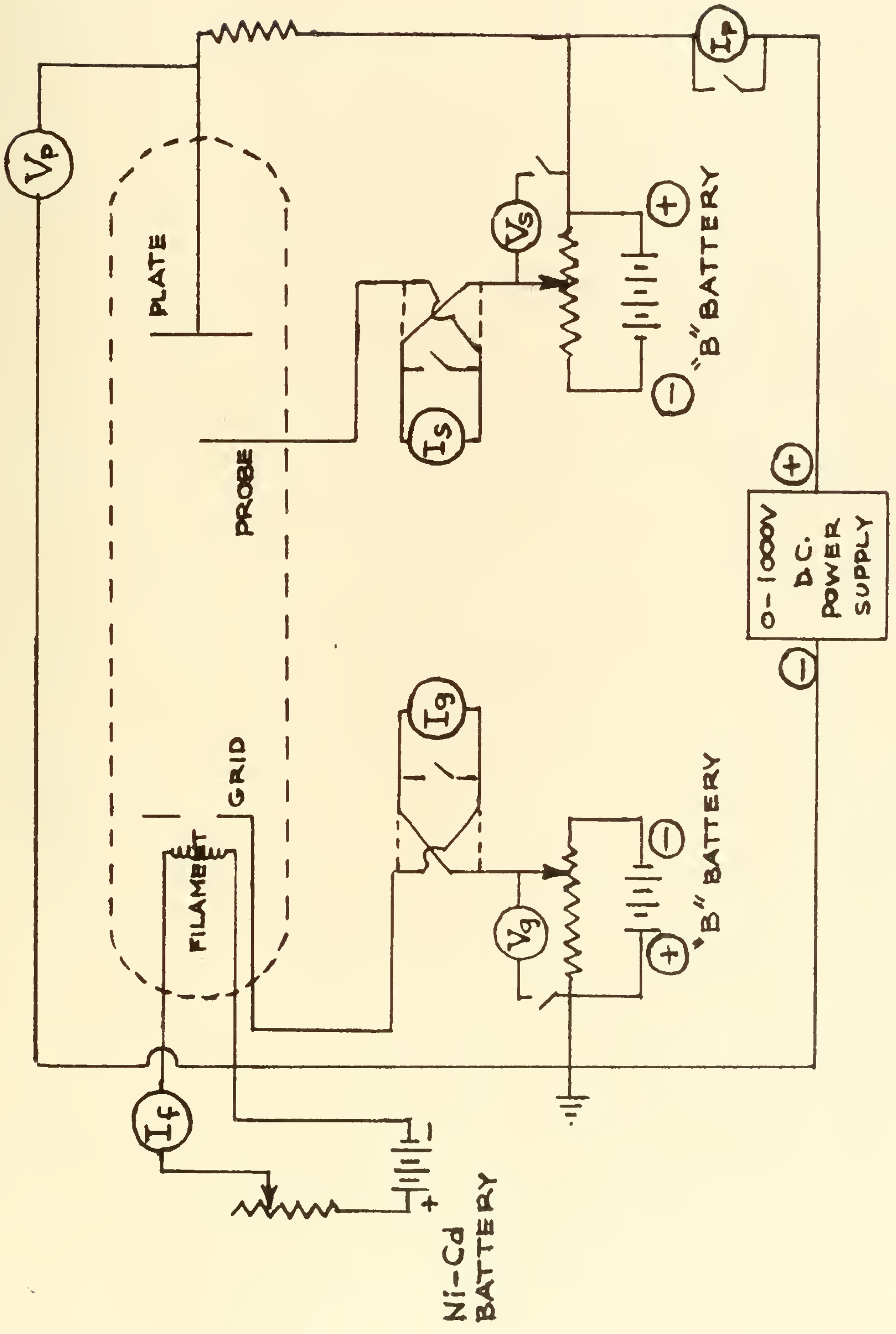
[18] H. T. Webb and Alan S. Garner, M. S. Thesis, pp. 22, U. S. Naval Postgraduate School, 1958

[19] Allen, op. cit., pp. 39

[20] G. Wehner and G. Medicus, Jour. Appl. Phys., 23, pp. 1037, September, 1952

FIG. 4



D.C. CIRCUITRY

either perpendicular or parallel to the discharge beam.

To provide for movement of the electrodes and probes with magnets, the electrodes and probes were attached to soft iron cylindrical cores sealed in glass. The grid to plate distance could be varied from zero to eight centimeters, and the probes could be placed in the discharge or withdrawn by means of magnets.

b. D. C. Circuits. The circuits used for control of the discharge and probe biasing are shown in Fig. 4. A voltage regulated power supply, manufactured by Kepco Laboratories, Model 1250B, was used as the main D. C. power supply for the tube potential. Power was available at zero to one thousand volts, at zero to five hundred milliamperes, regulated to three millivolts RMS. "B" batteries were used for the grid and probe biasing, and Nickel-Cadmium batteries were used for the filament heating.

A Hewlett-Packard, Model 410-B, high frequency vacuum tube volt meter was used to measure plate voltage.

c. Vacuum System. The ultra-vacuum system described by Alpert[21] was used as a pattern for the construction of this system. With it vacuums on the order of 10^{-10}mm of mercury or lower are obtainable. The two distinct features of the Alpert ultra-vacuum system are:

(1) Use of metal valves in lieu of stopcocks, which are one of the limiting factors of high vacuum.

(2) The Alpert ion gauge, which by minimizing the residual collector current due to soft x-rays, makes possible the

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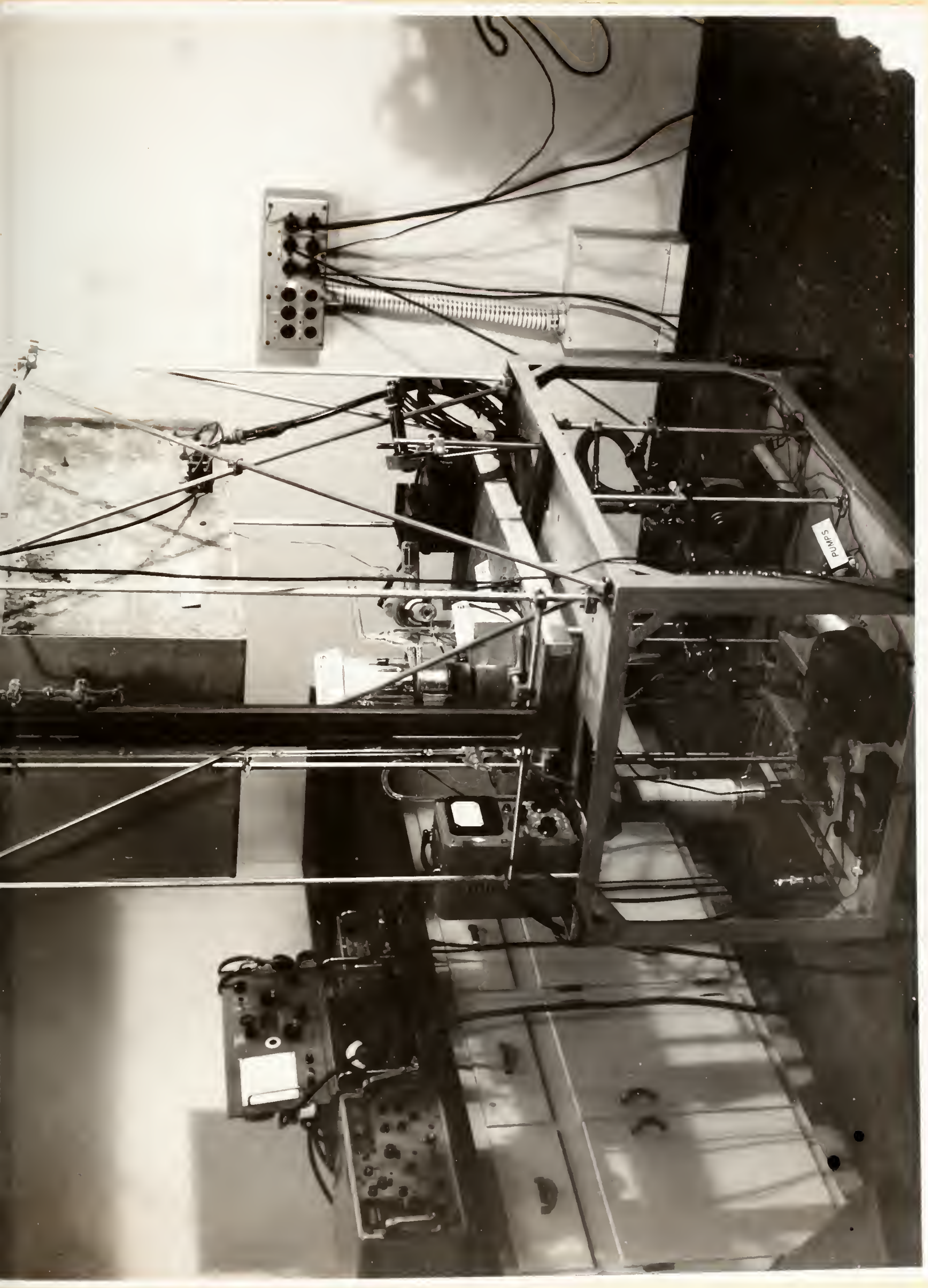
[21] D. Alpert, Jour. Applied Phys., 24, July, 1953

Fig. 5



GENERAL VIEW OF EQUIPMENT

measurement of ultra-vacuums. Fig. 6 is a schematic diagram of the vacuum system used.

Baking out of the system (except for the oil diffusion and fore-pumps) by means of a portable electric oven, considerably shortened the time required to achieve a high vacuum.

A Langmuir viscosity gauge[22], similar in design to the one constructed by Webb and Garner[23], was calibrated with a McLeod gauge and used to measure the gas pressure. The Langmuir viscosity gauge is unique in that it can be used to accurately determine pressures in the low micron range without introducing any contamination into the system.

d. Detection Equipment. Oscillations were detected and measured with four different pieces of equipment. Low frequencies were displayed on a Tektronix Type 551 Dual-Beam oscilloscope with a sweep speed of 0.02 micro seconds per centimeter and 0.05 volts per centimeter of trace. A radio receiving set, AN/SRR-13, was used to detect and measure oscillations in the range from two to thirty-two megacyles. This receiver has a built in calibration unit and a sensitivity of six micro volts, and frequency accuracy of plus or minus one per cent. The oscillation intensity was read as micro amps across a 600 ohm resistor and then converted to volts. A Gertsch Model FM-3 VHF frequency meter was used in an attempt to measure oscillation frequencies very accurately. This instrument has a frequency detection range of 20-1000 megacycles accurate to

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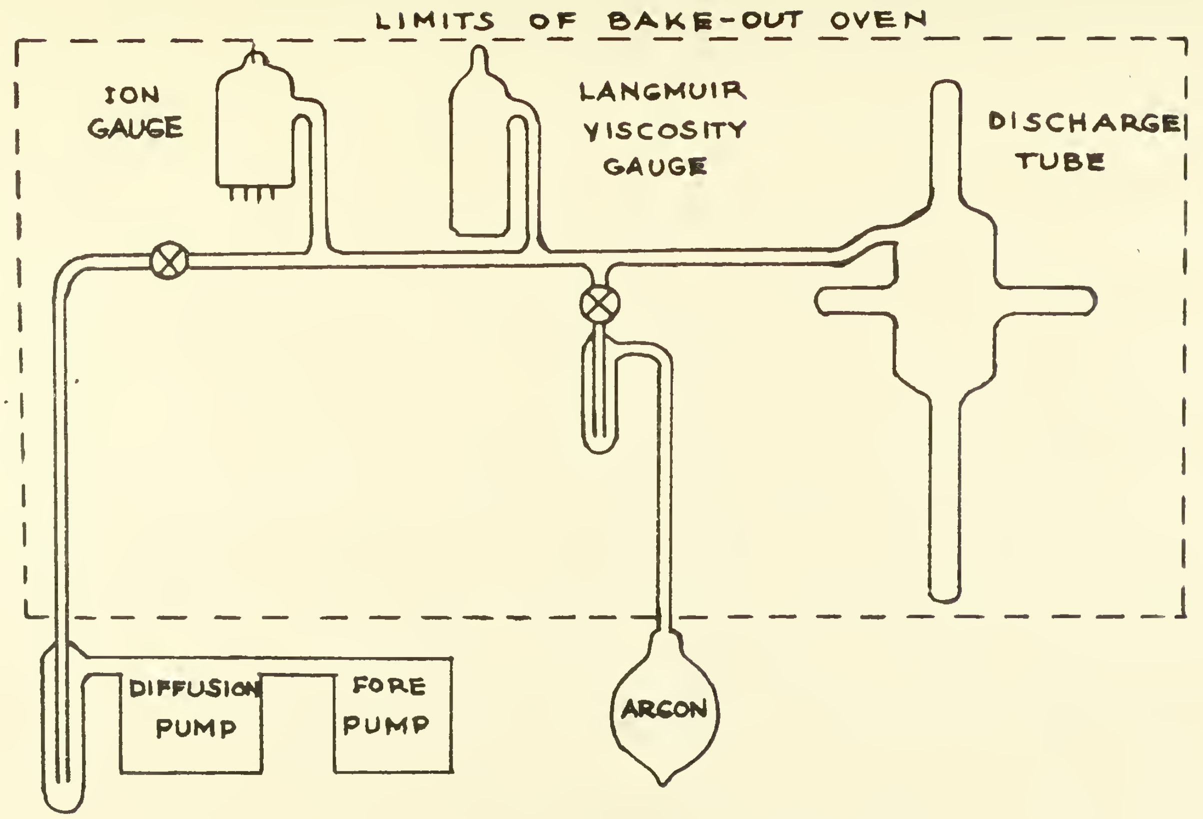
[22] J. Strong, et al, Procedures in Experimental Physics, pp. 146 Prentice-Hall, inc., 1945

[23] Webb and Garner, op. cit., pp29

FIG. 6



SCHEMATIC DIAGRAM OF VACUUM SYSTEM

plus or minus 0.001 per cent, but since it requires a threshold signal of ten milli-volts, this instrument was of little value for most signals were weaker than ten milli-volts. The instrument of most value in detecting and measuring high frequency oscillations was a radio test set, AN/URM-17, which was used as a sensitive radio frequency electronic micro-voltmeter. The URM-17 has a frequency range of from 370-1000 megacycles plus or minus 0.05 per cent and requires a threshold signal of ten micro-volts. The voltage readings must be considered relative since the instrument, which is calibrated for a matched imput impedance, was not so utilized.

4. Results

Following recognized vacuum techniques, the system was evacuated to the one micron range with a forepump. A three-stage glass diffusion pump further reduced the pressure to the 10^{-6}mm Hg range, whereupon the electrodes and probes were out-gassed with an induction heater. The system was then baked out by lowering an insulated oven (see Fig. 5) over the apparatus and heating the complete system, except for pumps and argon bottle, to 420°C. This temperature was maintained for thirty-six hours with intermittant degassing of the Veeco Ion Gauge. Following bake-out, the pressure was further reduced, by continued pumping with the diffusion pump in conjunction with the ion gauge, to 5×10^{-10}mm Hg whereupon the system was flushed out twice with argon and data runs begun. Two such flushings gave an estimated dilution factor of greater than 10^{14}.

For all data reported in this thesis the following tube parameters were maintained as indicated. The filament current for each run was kept at 4.0 amps. The grid voltage was maintained at -1 volt. Probe-to-grid and plate-to-grid measurements were made from the grid to the cathode side of the ring probe or plate respectively. For runs marked "probe withdrawn", the detection equipment leads were connected directly to the plate, otherwise all frequencies detected were taken from the ring probe. The needle probe was cleaned by induction heating and several trial runs attempted, but the response was so weak that use of the needle probe was abandoned in favor of the ring probe which gave far stronger signals. All pressures reported were measured with the viscosity gauge at room temperature (approx. 25°C) prior to tube operation. Low frequency oscillation amplitudes were measured in volts and high frequency amplitudes in micro volts and are placed in parentheses following oscillation frequencies on the graphs.

Efforts were first directed toward verifying the work of Webb and Garner.[24] During verification of their data, low frequency oscillations of very large amplitude (approx. 200 volts) were observed (see Fig. 8-15). These appeared on the same portion of the characteristic curve as the large amplitude oscillations obtained and reported by Webb and Garner, but were approximately three times as large. At Professor Oleson's suggestion, the D. C. circuits were varied in order to determine if plasma oscillations of this magnitude were indeed being developed in the tube or whether they were rather due to improper

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[24] Webb and Garner, op. cit., pp. 37

circuitry. Coaxial cables had been utilized and the series resistance was approximately six feet from the plate. Capacitance to ground had resulted in an RC time constant of the proper size for the tube to act as a relaxation oscillator. By varying the series resistance and introducing additional capacitance to ground, the cut off frequency for these relaxation oscillations was established (see Fig. 16). Once it had been determined that these very large amplitude oscillations were not true plasma oscillations, the circuit was altered to eliminate them. After shortening the length of all cables and placing the series resistance as close as possible to the plate, the relaxation oscillations were completely eliminated.

The parameters of pressure, interelectrode and probe-to-grid distances were systematically varied to determine optimum tube operating conditions for the generation of plasma oscillations in the low micron range. Over a pressure range from 1.5 - 25.75 micron oscillation conditions were maximized at 4.55 microns. Optimum interelectrode and probe distances in general differed for the various pressures but for the 4.55 micron run these distances were respectively 15.5mm and 0.8mm. In general, the number and intensity of oscillations increased the closer the probe approached the cathode (compare fig. 18 and fig. 20) which correlates, as expected, with previously noted results. Attainment of closer probe-cathode distances was prevented by the grid ring which is located approximately 8mm in front of the filament.

Low frequency oscillations from 40 KC to 32 MC were observed as

well as high frequencies from 370 MC - 1015 MC using detection equipment previously described. Low frequency amplitudes were several orders of magnitude higher than those at high frequencies. Attenuation of the high frequencies by losses in the iron cores provided for probe movement may possibly account for this. Specific data for all runs made is tabulated on individual graphs (Fig. 17 thru Fig. 30) a summary of which is presented on page 28 (Fig.7). Pictures of oscillographs of typical low frequency oscillations are presented in Fig. 37 and 38.

Probe characteristic curves were determined for two pressures and seven probe-to-grid distances. Fig. 33 is a plot of the probe characteristic curves for 4.55 micron pressure, plate-to-grid separation of 15.5mm, and probe-to-grid distances of 0.8mm, 4.8mm, and 7.7mm. Fig 35 is a plot of the probe characteristic curve for 8.0 micron pressure, plate-to-grid separation of 15.5mm, and probe-to-grid distances of 1.0mm, 2.5mm, 4.8mm and 8.2mm. Fig. 34 and Fig. 36 are plots of electron current versus probe voltage (relative to anode) for 4.55 micron and 8.0 micron respectively. The curves were analyzed by the method of Langmuir and Mott-Smith[25] and the data obtained therefrom are summarized in Fig. 31.

In general the probe work was not satisfactory, but some information was obtained. All probe characteristic curves indicated that high energy scattering, which has been associated with plasma oscillation, was occurring, since the plots indicate that there were present in the discharge, electrons with energies approximately one to seven volts greater than the cathode-plate potential. As previously noted,

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[25] Langmuir and Mott-Smith, op. cit., pp. 538

most of the voltage fall occurs near the cathode, and all of the plasma potentials measured tend to confirm this generalization. Since the grid is eight millimeters from the cathode, it was impossible to measure the plasma potential close to the cathode. All results obtained indicated that nearly all of the voltage fall occurred between the grid and cathode.

By applying the electron density obtained from the probe analysis to the Langmuir-Tonks plasma frequency equations[26], frequencies for the electron and positive ion oscillations were predicted. A comparison of calculated oscillation frequencies and those observed shows agreement only in order of magnitude. If calculated frequencies were correct, observed frequencies were harmonics, but this was probably not the case. Fig. 32, from Allen[27], gives an indication of the extent of distortion attributable to probe disturbance of the plasma. More likely than not, the lack of correlation between predicted and observed frequencies is due to such an effect. Likewise, errors in the computation of electron temperatures would be expected due to this disturbance.

An attempt was made to observe variations of oscillation intensity with interelectrode distance as described by Mahaffey and Emeleus.[28] The high intensity of oscillations, depicted in their graph of Intensity vs Interelectrode Distance, occuring at a distance of about 1 cm from the cathode, was not seen in our investigation. Again, the inability to

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[26] Tonks and Langmuir, op. cit., pp. 1219

[27] Allen, op. cit., p. 63

[28] D. W. Mahaffey and K. G. Emeleus, Jour. of Elec. and Control, Vol. 4, No. 4, April, 1958

get closer to the cathode than the grid ring allowed, probably prevented corroborating data being obtained. Oscillation intensities did not vary significantly over the range examined (1.8mm - 86.0mm grid-to-plate separation). Supression of oscillations by shortening the inter-electrode distance also reported by the above workers was tried, but without success, because of the reason just mentioned.

K. G. Emeleus and T. K. Allen[29] in 1955 were unable to detect electro-magnetic radiation with the Langmuir frequency, or its harmonics, coming direct from a plasma in which high frequency oscillations are taking place. They postulated that the energy outside the tube is much less than the corresponding oscillatory currents which can be withdrawn by an internal probe. The present workers were able to detect electro-magnetic radiation of 400-800 MC frequency with the AN/URM-17 without connecting it to an internal probe, but with the detector leads approximately six inches from the probe. The intensity of these oscillation was approximately doubled when the URM was connected to the internal probe. Probably the radiation detected was due to the probe acting as an antenna.

5. Conclusions

In view of (1) multiple frequency oscillations observed at the various probe and interelectrode settings (rather than large amplitude, single frequency oscillations at each setting); (2) the absence of peaked oscillation intensities as near to the cathode as the tube

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[29] K. G. Emeleus and T. K. Allen, Australian Jour. of Phys., Vol. 8, No. 2, 1955

configuration permitted, and (3) the general low amplitude of those oscillations obtained, it must be concluded that true plasma oscillations were probably not detected in the tube used for this investigation. What was observed was, perhaps instead secondary oscillations due to reflections from the tube walls and the face of the anode. As remarked before in this report, the presence of the grid 8mm in front of the filament prevented measurements of plasma oscillations precisely in the region where they are most apt to occur. Further, the assymetrical shape of the tungsten filament was not conducive to the emission of anything like a coherent, collimated beam of electrons but rather emitted diffuse, divergent rays of electrons which were free to reflect in random fashion off the tube walls.

Appreciable attenuation of those oscillations picked up by the probe was introduced by the coiled probe leads inside the tube which, as Dr. T. K. Allen has pointed out, had the effect of an RF choke coil. Also the ring probe was far too massive for the purpose intended, the dimensions in cross section being on the order of a wave length of the frequencies of interest. The physical disturbance of the plasma by the probe must be accepted in probe work, but in this instance a more delicately constructed probe could materially reduce the degree of disturbance.

It is questionable whether the high degree of purity derived from evacuating the system to the 10^{-10}mm Hg range warranted the time and effort required to obtain it. Pressures of 10^{-7}mm Hg followed by several flushings with argon would probably be just as suitable, providing the system was tight.

The conclusion is therefore, that the tube as presently designed is not suitable for detecting true plasma oscillations in the region

where they are found and that such oscillations as are presently capable of being detected in it are really due to secondary effects.

6. Recommedations for further work

a. Accordingly, the following recommendations for modifying the tube are made:

(1) Replace the present cathode with a flat, disk-type, oxide coated tungsten cathode requiring lower filament current. This lower current should reduce the intense light of the present filament and permit visible examination of the discharge.

(2) Remove the grid and the quartz shade so that the region adjacent to the cathode can be investigated. A movable grid could be useful in modulation experiments.

(3) Install a single loop ring-probe of the same diameter but made of much finer wire (approx. 0.25mm wire). .01"

(4) Do away with the present arrangement for probe movement so as to eliminate coiled loops of slack wire which attenuate oscillation signals. Use instead the arrangement suggested by Allen whereby movement is controlled externally through a system of vacuum seals so that coils of lead wires will be eliminated. However before this is done, data should be obtained in the region very close to the cathode to determine the effect of high purity.

(b) With the tube modified as suggested above, conduct an experiment using the ring probe as the anode, the plate as a

repeller and determine whether the needle probe will detect coherent reflections and secondary emission from the plate.

If a movable grid is available, the effect of a modulation produced by varying the grid voltage should be studied.

Also investigate the presence of moving striations in the tube with a photomultiplier arrangement to determine whether they are associated with the low frequency oscillations.

Fig. 7

SUMMARY OF TUBE CHARACTERISTIC CURVES

Pressure (microns)	Plate-To-Grid Distance (mm)	Probe-to-Grid Distance (mm)	Fig. Number	Page Number
1.5	5.1	—	10	31
2.2	3.6	—	11	32
2.2	6.2	—	12	33
2.2	16.1	—	13	34
4.55	15.5	—	17	38
4.55	15.5	0.8	18	39
4.55	15.5	4.8	19	40
4.55	15.5	7.7	20	41
4.55	15.5	8.2	21	42
6.4	18.76	—	8	29
6.4	18.76	2.01	9	30
6.6	18.76	—	22	43
8.0	15.5	1.0	23	44
8.0	15.5	2.5	24	45
8.0	15.5	4.8	25	46
10.2	2.5	—	14	35
10.2	6.4	—	15	36
11.1	85.2	—	26	47
11.1	15.0	2.0	27	48
11.1	15.0	5.0	28	49
11.1	15.0	8.0	29	50
12.9	18.76	—	30	51

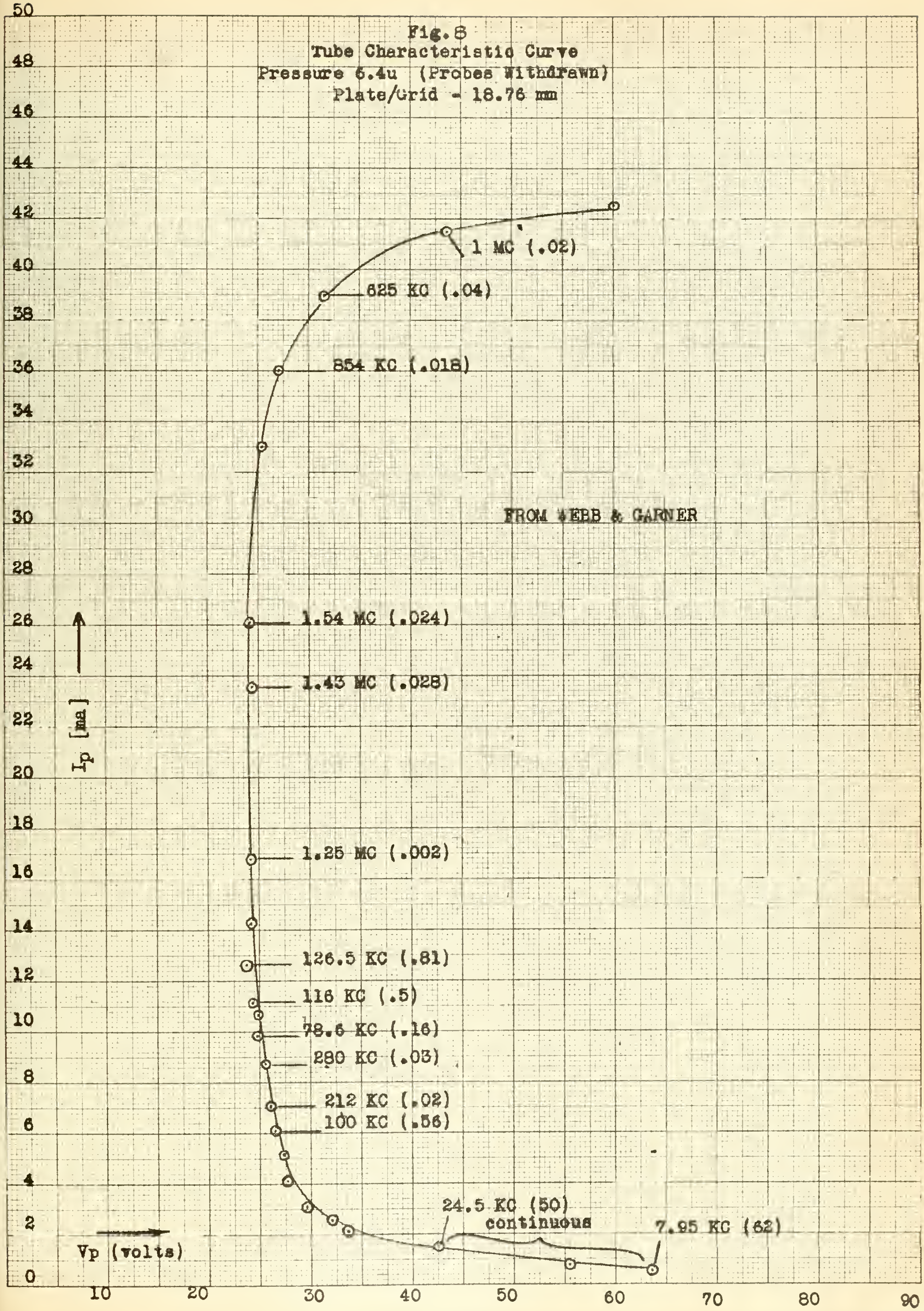


Fig. 8
Tube Characteristic Curve
Pressure 6.4u (Probes Withdrawn)
Plate/Grid - 18.76 mm

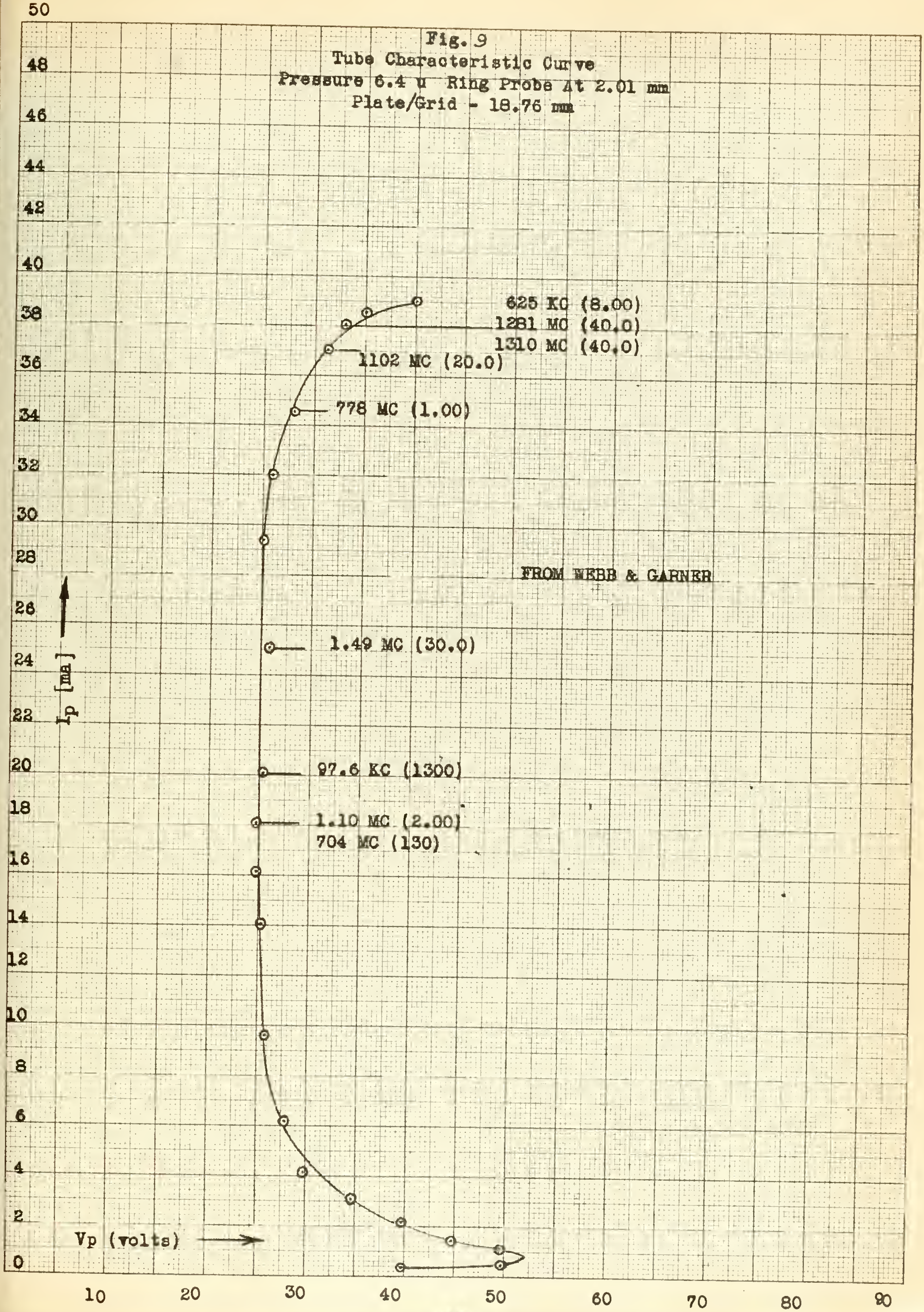


Fig. 9
Tube Characteristic Curve
Pressure 6.4 u Ring Probe At 2.01 mm
Plate/Grid - 18.76 mm

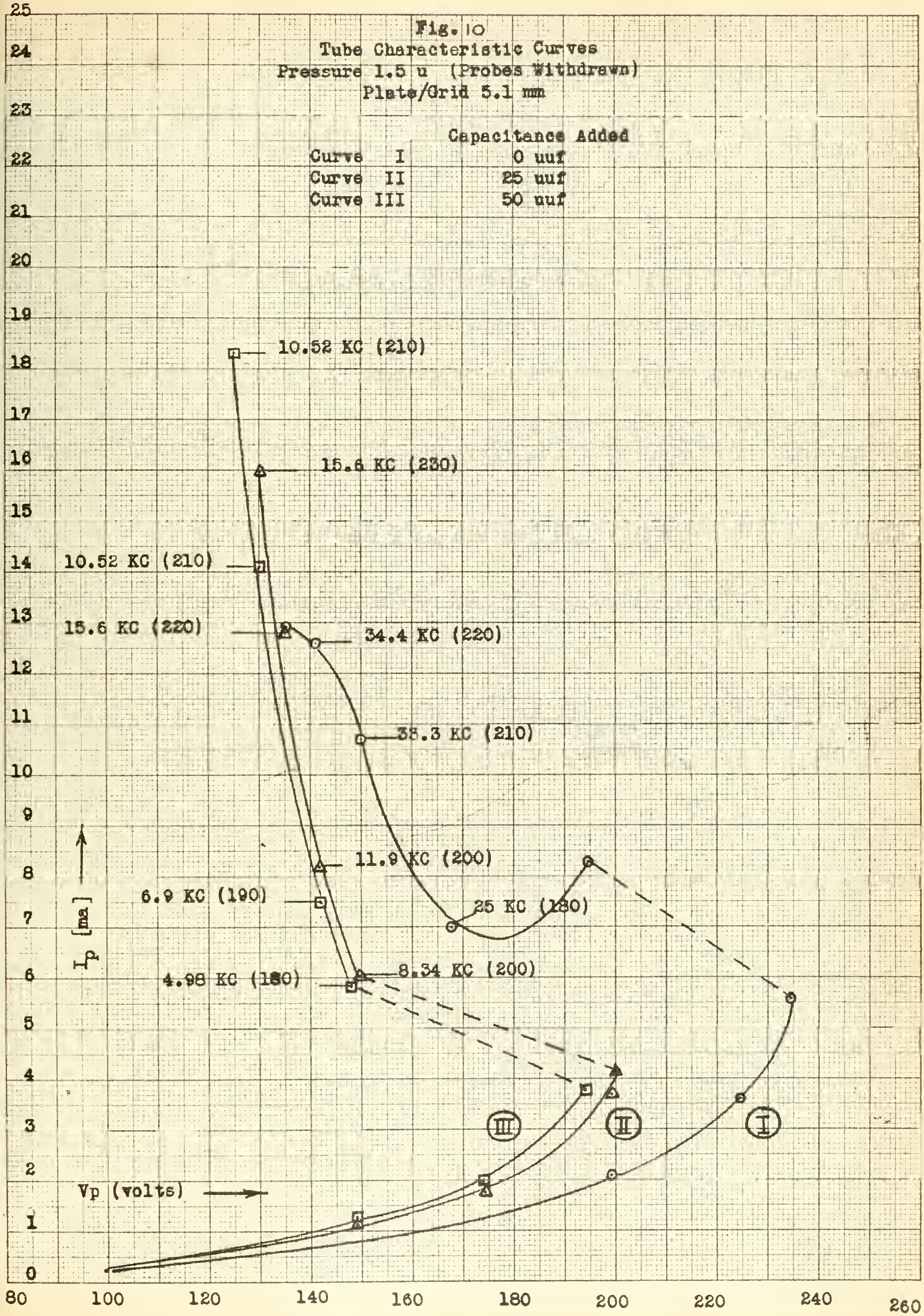


Fig. 10
Tube Characteristic Curves
Pressure 1.5 u (Probes Withdrawn)
Plate/Grid 5.1 mm

		Capacitance Added
Curve	I	0 uuf
Curve	II	25 uuf
Curve	III	50 uuf

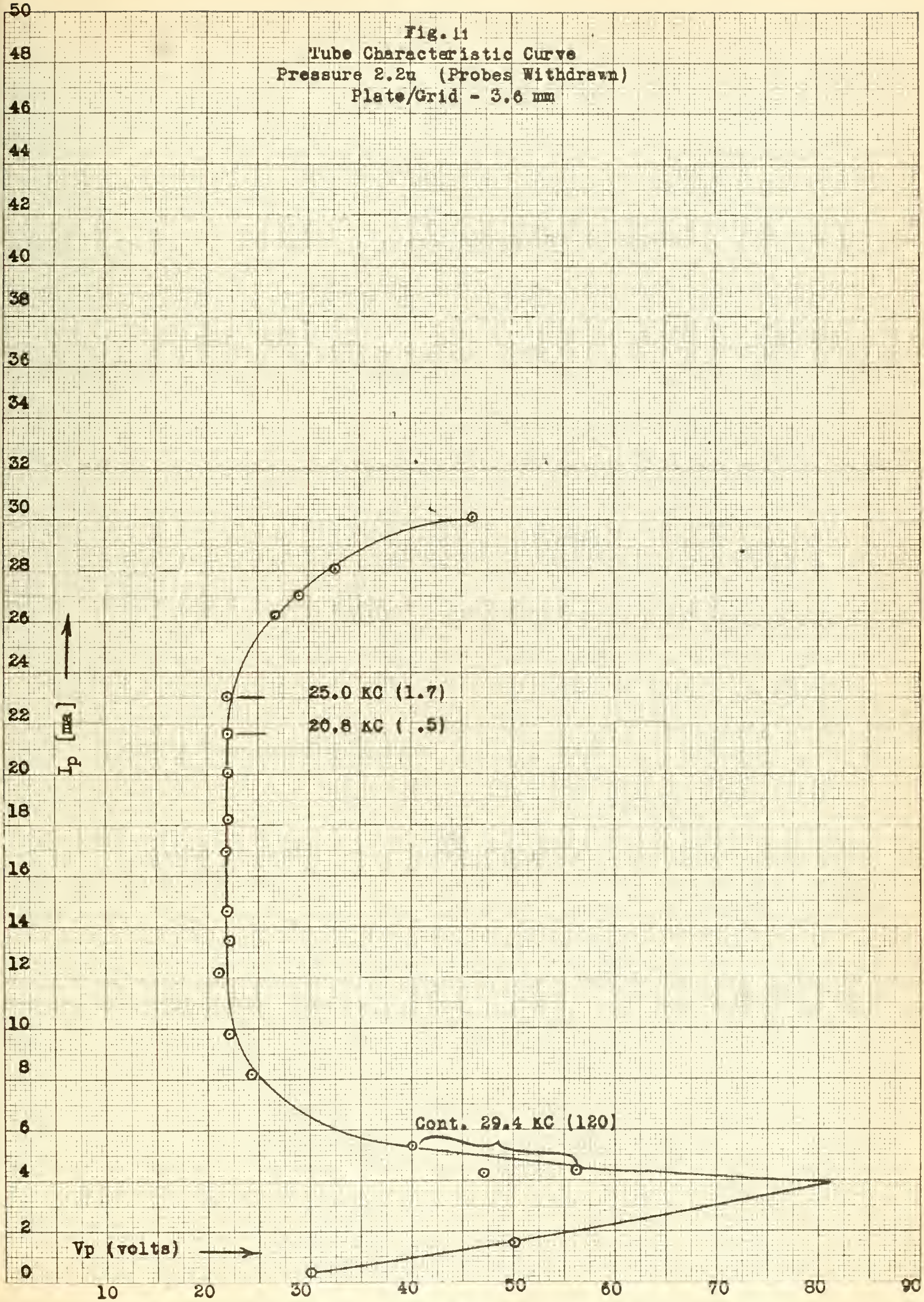


Fig. 11
Tube Characteristic Curve
Pressure 2.2u (Probes Withdrawn)
Plate/Grid - 3.6 mm

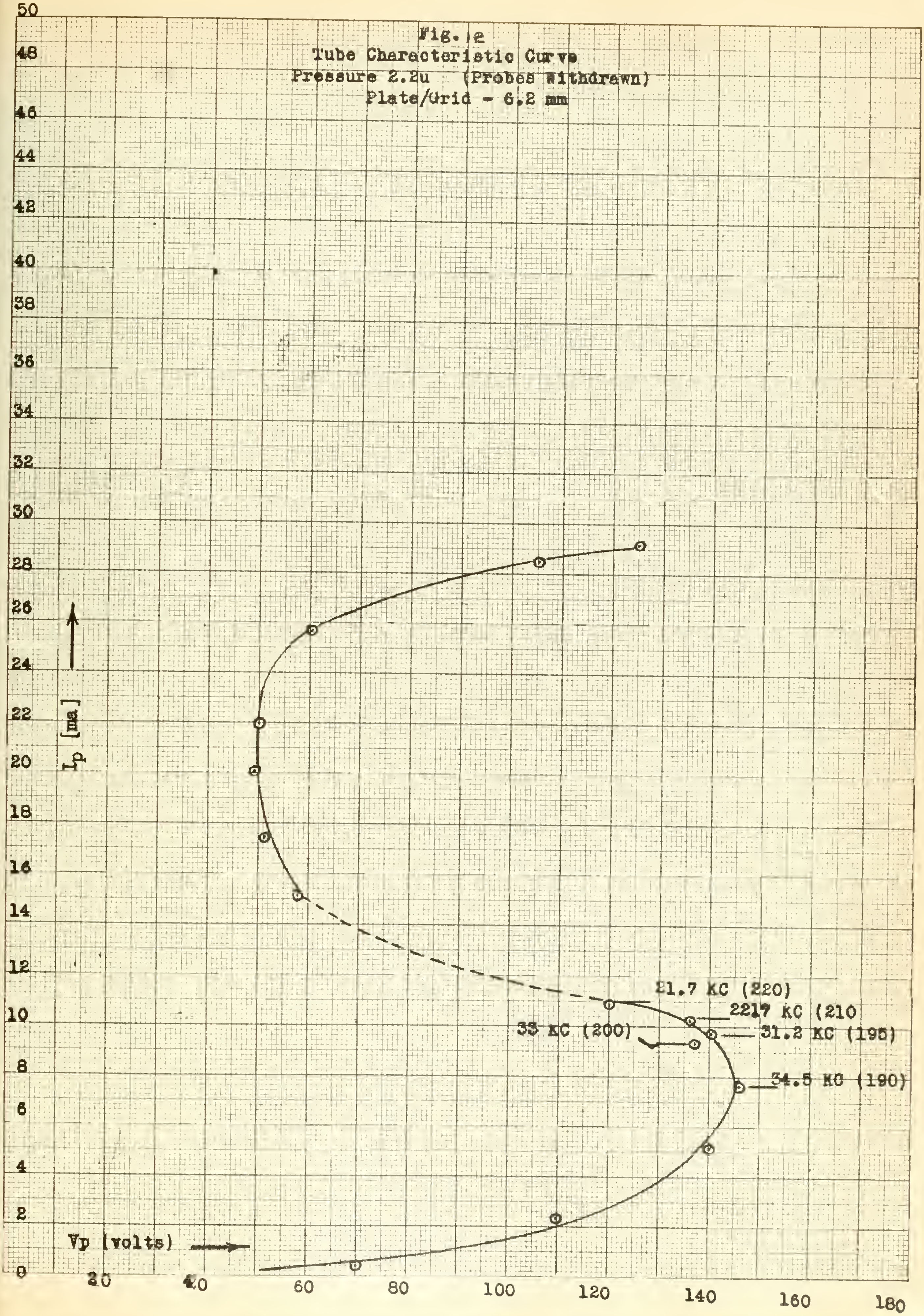


Fig. 12
Tube Characteristic Curve
Pressure 2.2u (Probes Withdrawn)
Plate/Grid - 6.2 mm

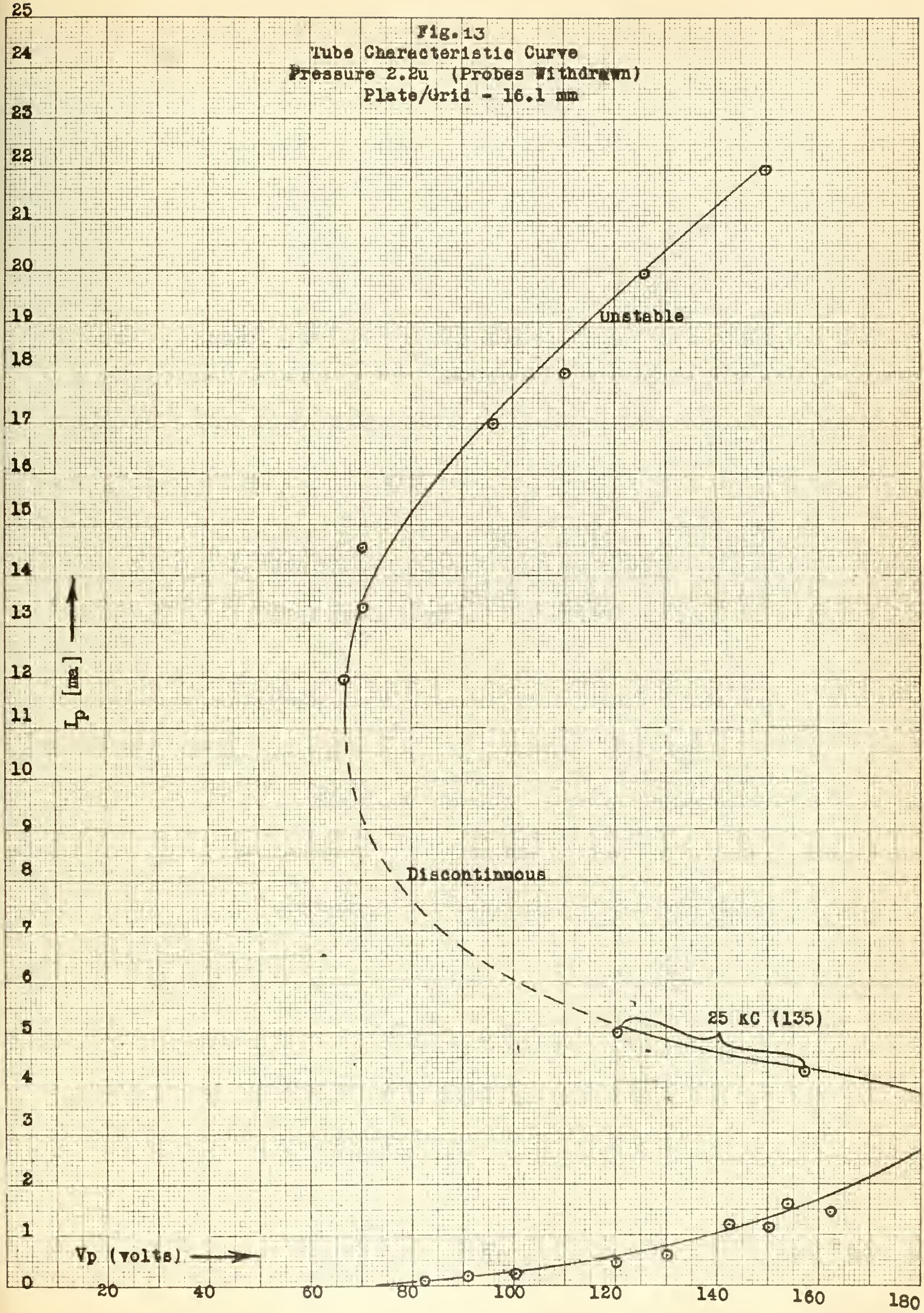


Fig. 13
Tube Characteristic Curve
Pressure 2.2u (Probes Withdrawn)
Plate/Grid - 16.1 mm

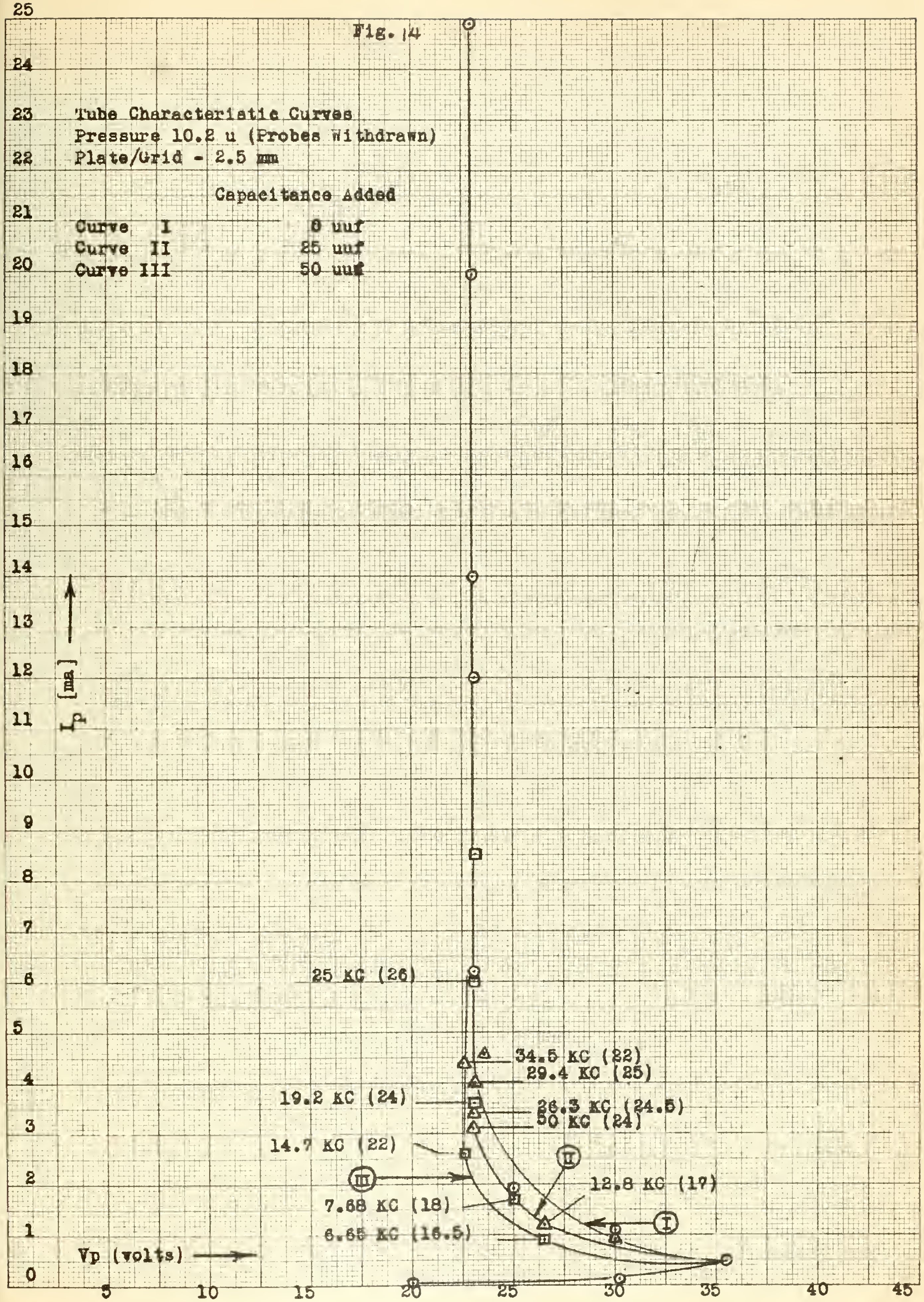
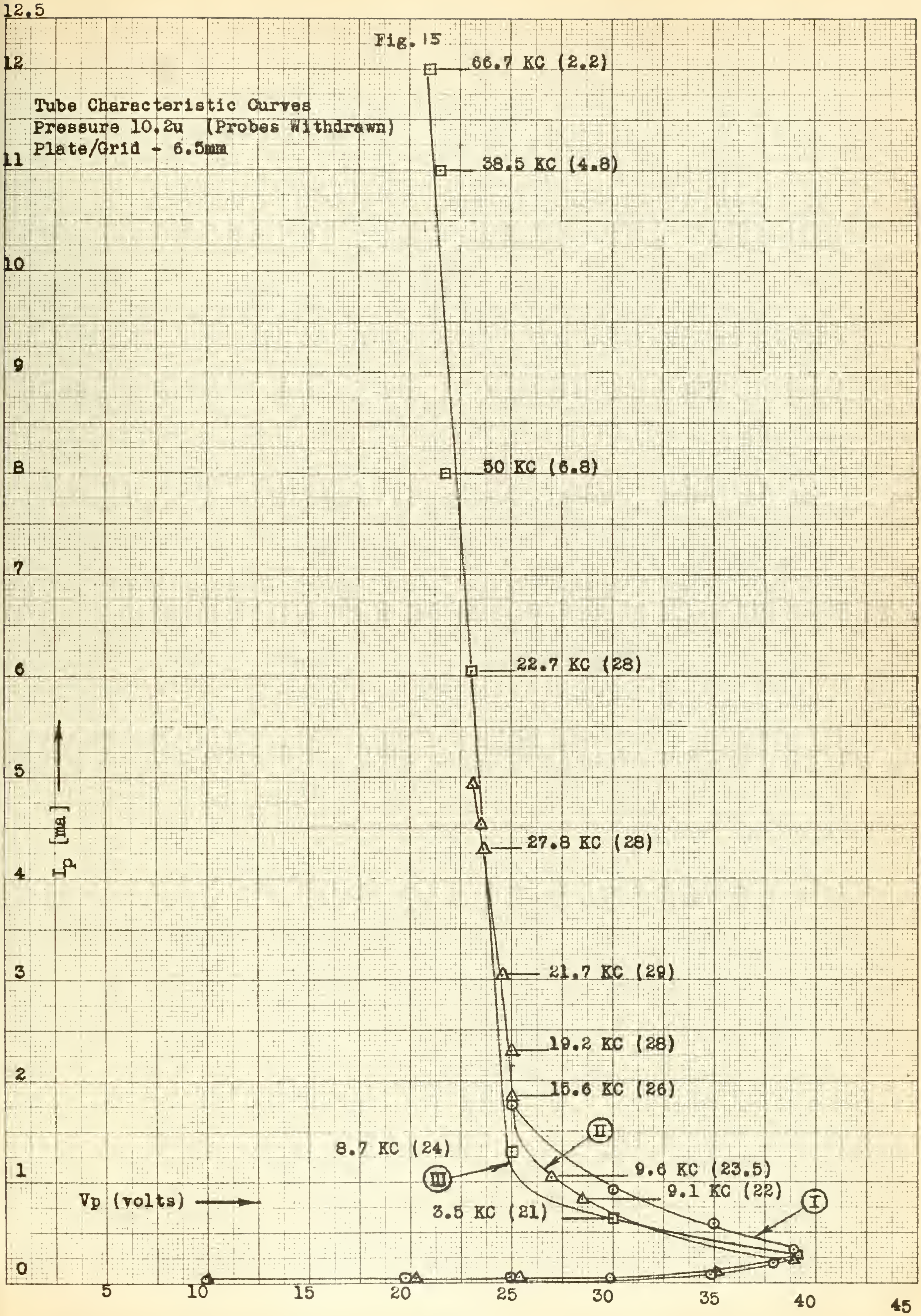


Fig. 14

Tube Characteristic Curves
Pressure 10.2 u (Probes Withdrawn)
Plate/Grid - 2.5 mm
Capacitance Added
Curve I 0 uuf
Curve II 25 uuf
Curve III 50 uuf
25 KC (26)
34.5 KC (22)
29.4 KC (25)
19.2 KC (24)
26.3 KC (24.5)
50 KC (24)
14.7 KC (22)
III
II
12.8 KC (17)
7.68 KC (18)
I
6.65 KC (16.5)
I_p [ma]
Vp (volts)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
5
10
15
20
25
30
35
40
45

Fig. 15



Tube Characteristic Curves
Pressure 10.2u (Probes Withdrawn)
Plate/Grid - 6.5mm

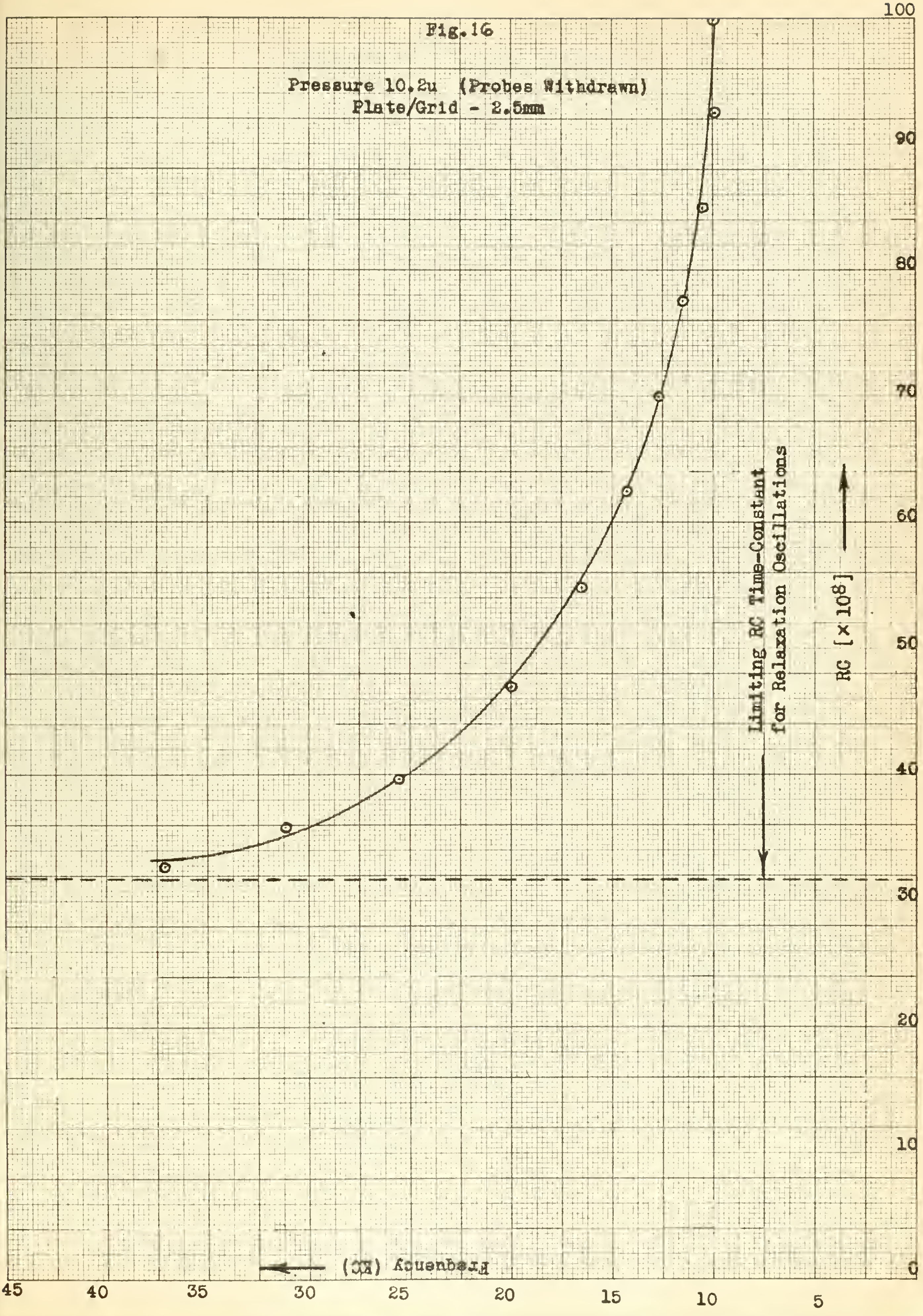


Fig.16

Pressure 10.2u (Probes Withdrawn)
Plate/Grid - 2.5mm
Limiting RC Time-Constant for Relaxation Oscillations
RC [x 10^8]
Frequency (KC)
100
90
80
70
60
50
40
30
20
10
0
45
40
35
30
25
20
15
10
5

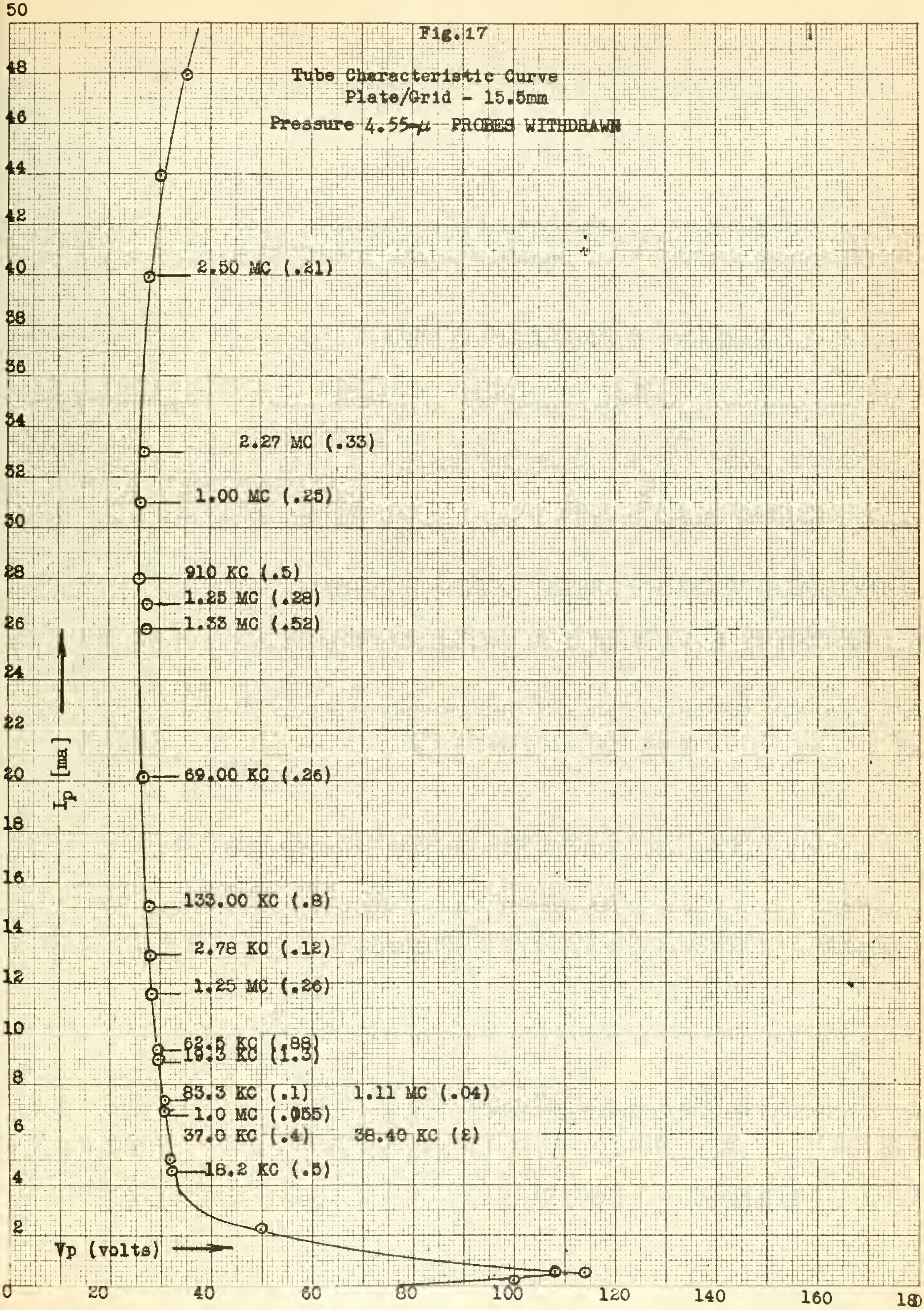


Fig. 17

Tube Characteristic Curve
Plate/Grid - 15.5mm
Pressure 4.55 μ PROBES WITHDRAWN

Fig. 18

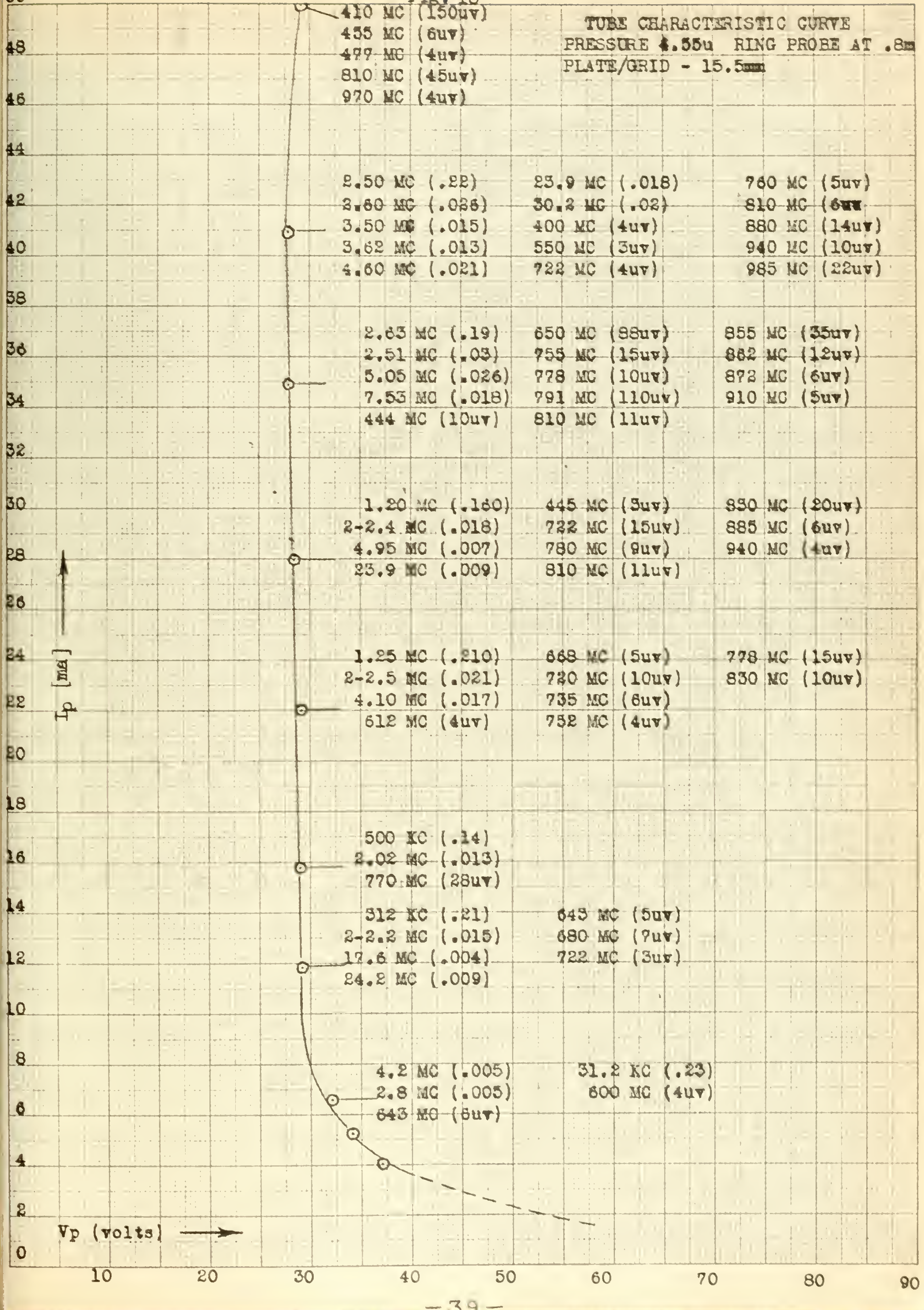
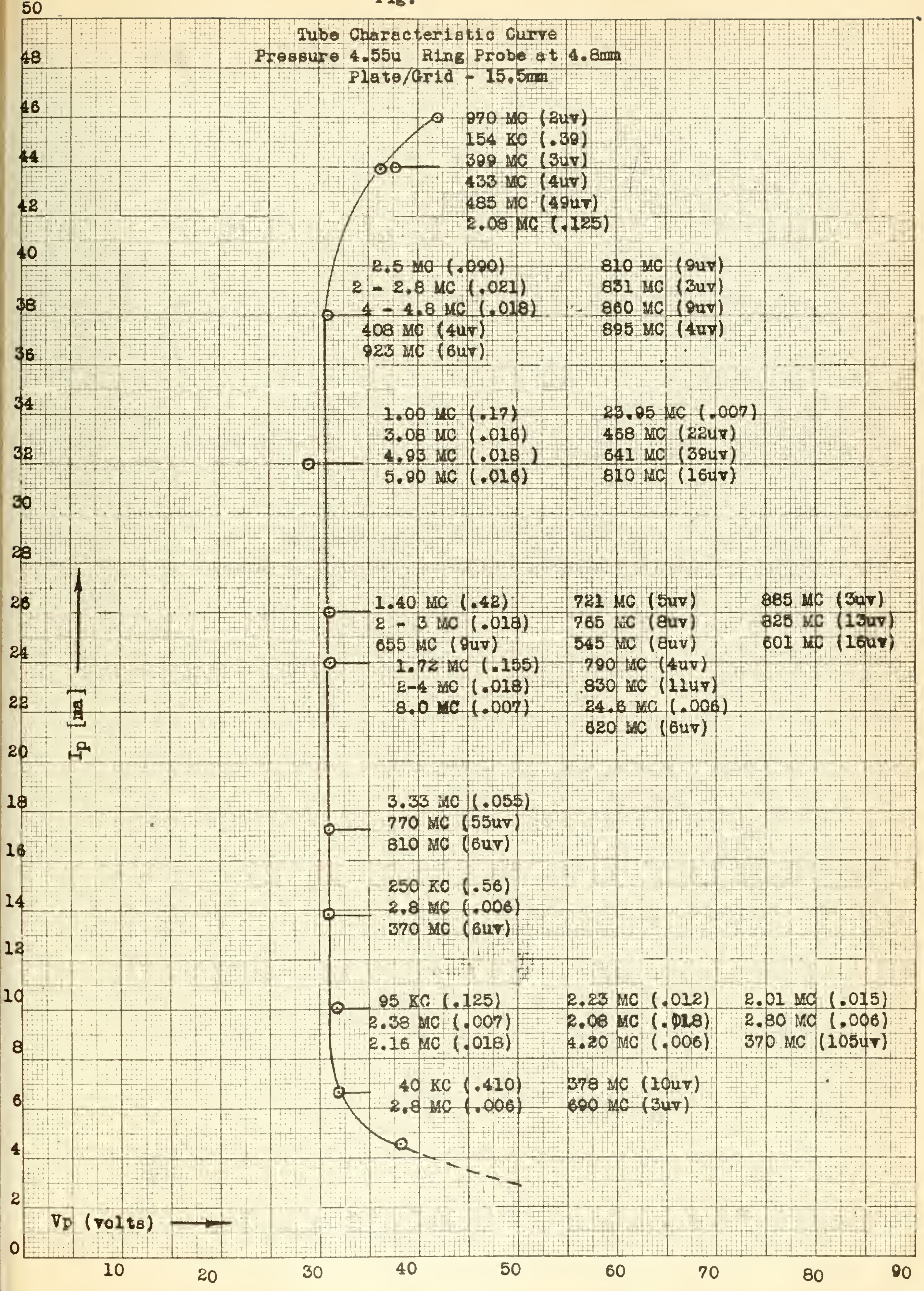

TUBE CHARACTERISTIC CURVE
PRESSURE 4.55u RING PROBE AT .8m
PLATE/GRID - 15.5mm
410 MC (150uv)
455 MC (6uv)
477 MC (4uv)
810 MC (45uv)
970 MC (4uv)
2.50 MC (.22)
2.60 MC (.026)
3.50 MC (.015)
3.62 MC (.013)
4.60 MC (.021)
23.9 MC (.018)
30.2 MC (.02)
400 MC (4uv)
550 MC (3uv)
722 MC (4uv)
760 MC (5uv)
810 MC (6uv
880 MC (14uv)
940 MC (10uv)
985 MC (22uv)
2.63 MC (.19)
2.51 MC (.03)
5.05 MC (.026)
7.53 MC (.018)
444 MC (10uv)
650 MC (88uv)
755 MC (15uv)
778 MC (10uv)
791 MC (110uv)
810 MC (11uv)
855 MC (35uv)
862 MC (12uv)
872 MC (6uv)
910 MC (5uv)
1.20 MC (.160)
2-2.4 MC (.018)
4.95 MC (.007)
23.9 MC (.009)
445 MC (5uv)
722 MC (15uv)
780 MC (9uv)
810 MC (11uv)
830 MC (20uv)
885 MC (6uv)
940 MC (4uv)
1.25 MC (.210)
2-2.5 MC (.021)
4.10 MC (.017)
612 MC (4uv)
668 MC (5uv)
720 MC (10uv)
735 MC (6uv)
752 MC (4uv)
778 MC (15uv)
830 MC (10uv)
500 KC (.14)
2.02 MC (.013)
770 MC (28uv)
312 KC (.21)
2-2.2 MC (.015)
17.6 MC (.004)
24.2 MC (.009)
645 MC (5uv)
680 MC (7uv)
722 MC (3uv)
4.2 MC (.005)
2.8 MC (.005)
643 MC (6uv)
31.2 KC (.23)
600 MC (4uv)
Ip [ma]
Vp (volts)
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90

Fig. 19


Tube Characteristic Curve
Pressure 4.55u Ring Probe at 4.8mm
Plate/Grid - 15.5mm
970 MC (2uv)
154 KC (.39)
399 MC (3uv)
433 MC (4uv)
485 MC (49uv)
2.08 MC (.125)
2.5 MC (.090)
2 - 2.8 MC (.021)
4 - 4.8 MC (.018)
408 MC (4uv)
923 MC (6uv)
810 MC (9uv)
831 MC (3uv)
860 MC (9uv)
895 MC (4uv)
1.00 MC (.17)
3.08 MC (.016)
4.93 MC (.018)
5.90 MC (.016)
23.95 MC (.007)
468 MC (22uv)
641 MC (39uv)
810 MC (16uv)
1.40 MC (.42)
2 - 3 MC (.018)
655 MC (9uv)
721 MC (5uv)
765 MC (8uv)
545 MC (8uv)
885 MC (3uv)
825 MC (13uv)
601 MC (16uv)
1.72 MC (.155)
2-4 MC (.018)
8.0 MC (.007)
790 MC (4uv)
830 MC (11uv)
24.6 MC (.006)
620 MC (6uv)
3.33 MC (.055)
770 MC (55uv)
810 MC (6uv)
250 KC (.56)
2.8 MC (.006)
370 MC (6uv)
95 KC (.125)
2.38 MC (.007)
2.16 MC (.018)
2.23 MC (.012)
2.08 MC (.018)
4.20 MC (.006)
2.01 MC (.015)
2.80 MC (.006)
370 MC (105uv)
40 KC (.410)
2.8 MC (.006)
378 MC (10uv)
690 MC (3uv)
I_p [ma]
Vp (volts)
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90

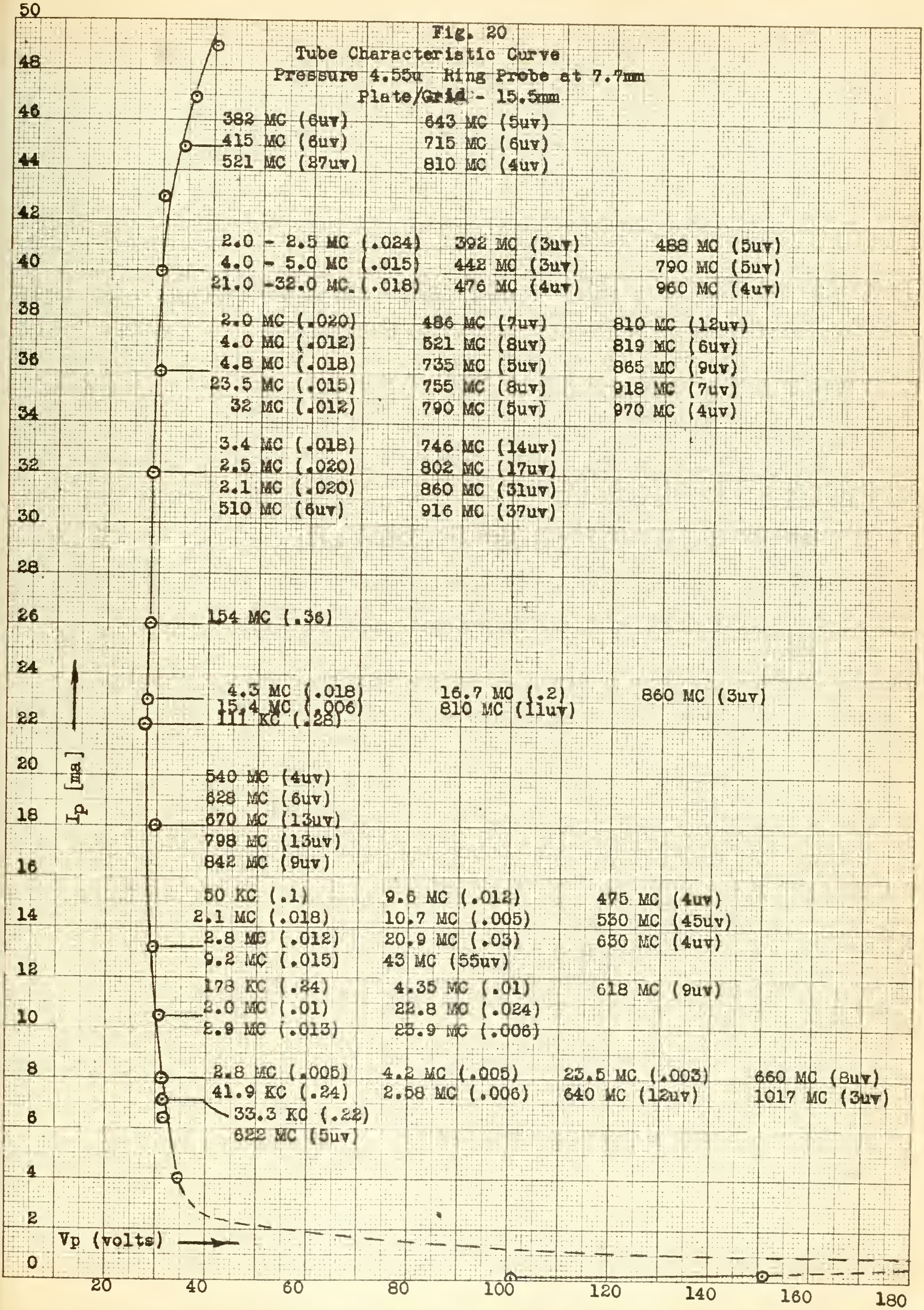
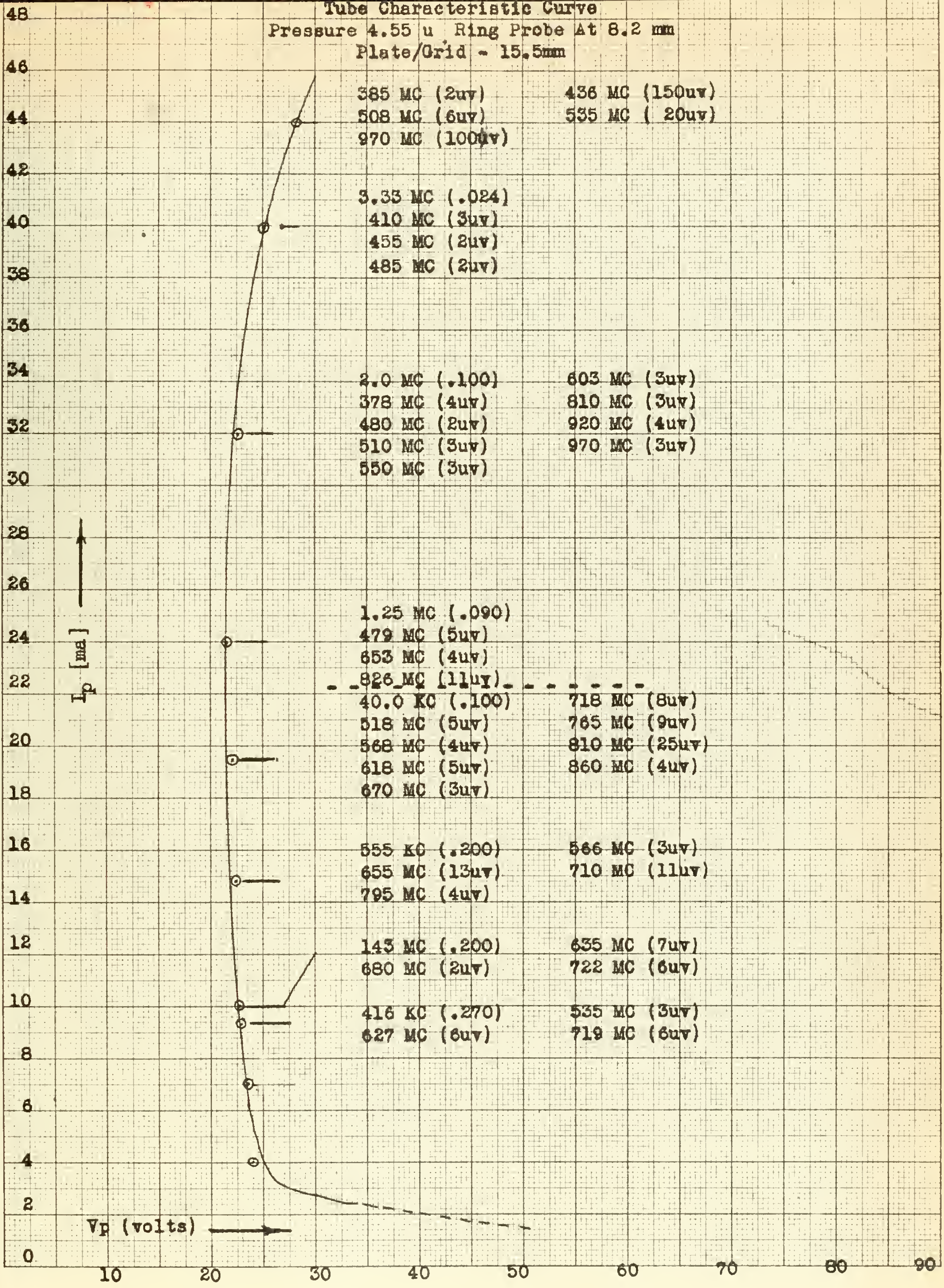


Fig. 20
Tube Characteristic Curve
Pressure 4.55u Ring Probe at 7.7mm
Plate/Grid - 15.5mm



Tube Characteristic Curve
Pressure 4.55 u Ring Probe At 8.2 mm
Plate/Grid - 15.5mm

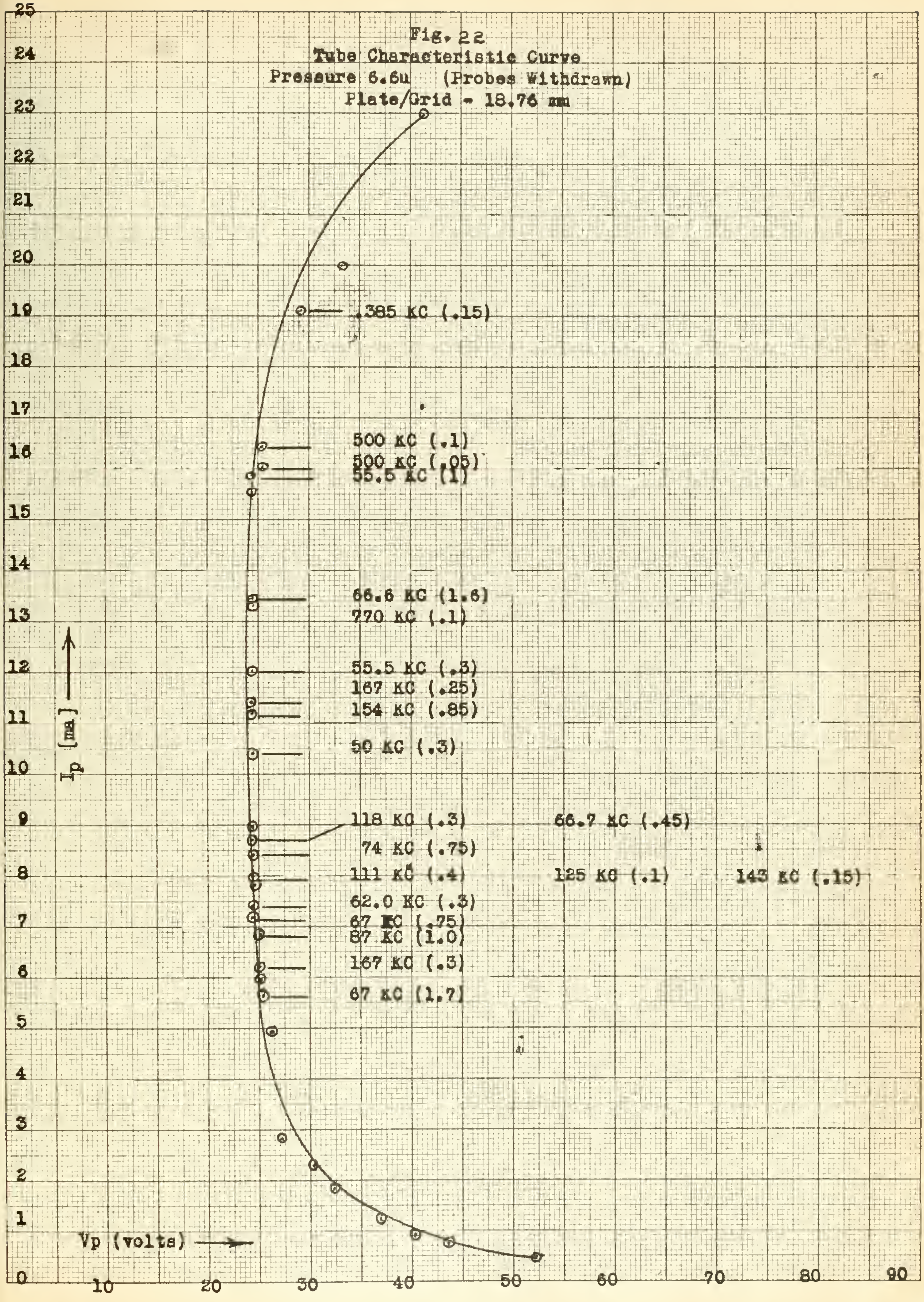


Fig. 22
Tube Characteristic Curve
Pressure 6.6u (Probes Withdrawn)
Plate/Grid - 18.76 mm

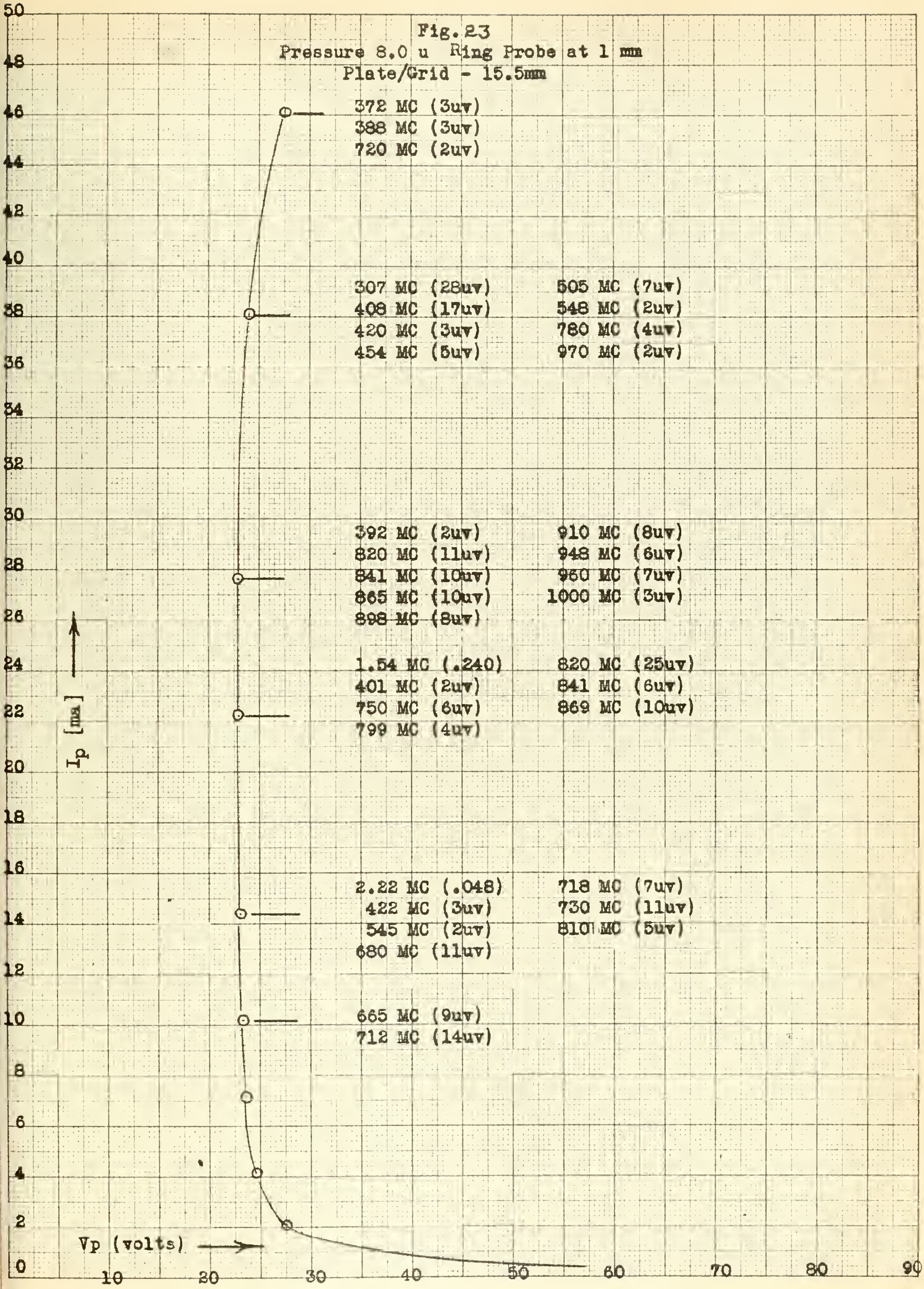


Fig. 23
Pressure 8.0 u Ring Probe at 1 mm
Plate/Grid - 15.5mm

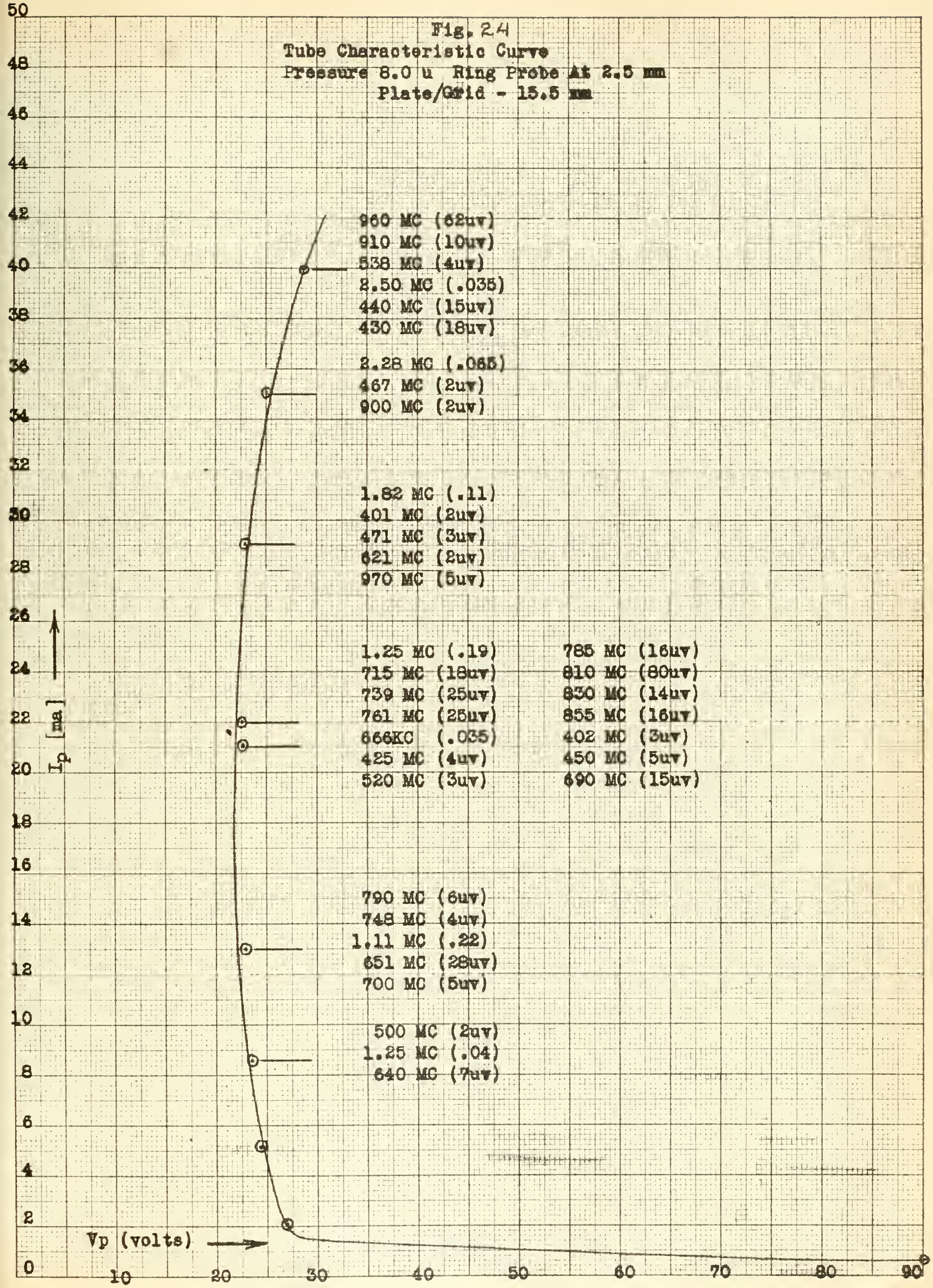


Fig. 24
Tube Characteristic Curve
Pressure 8.0 u Ring Probe At 2.5 mm
Plate/Grid - 15.5 mm

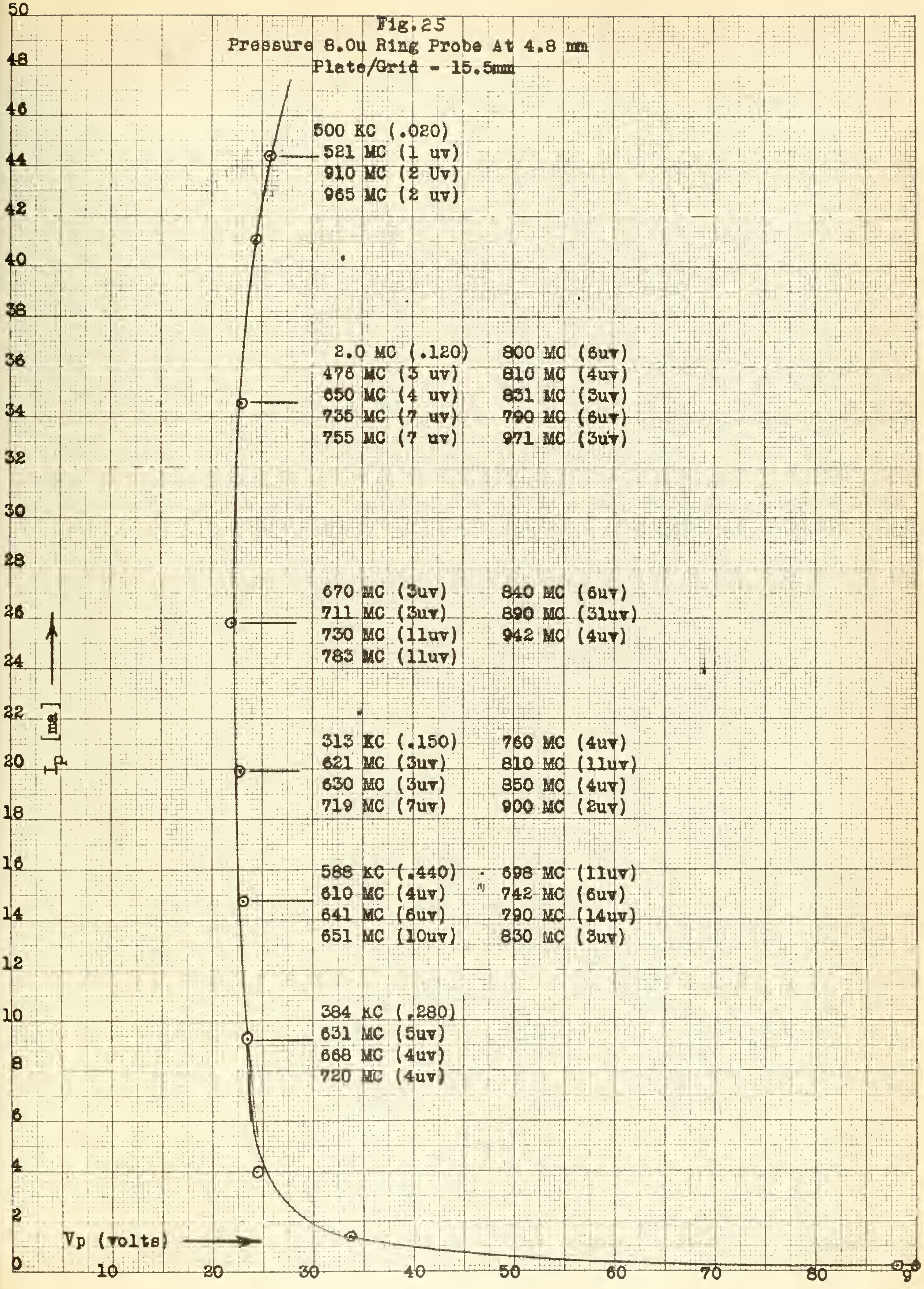


Fig.25
Pressure 8.0u Ring Probe At 4.8 mm
Plate/Grid - 15.5mm

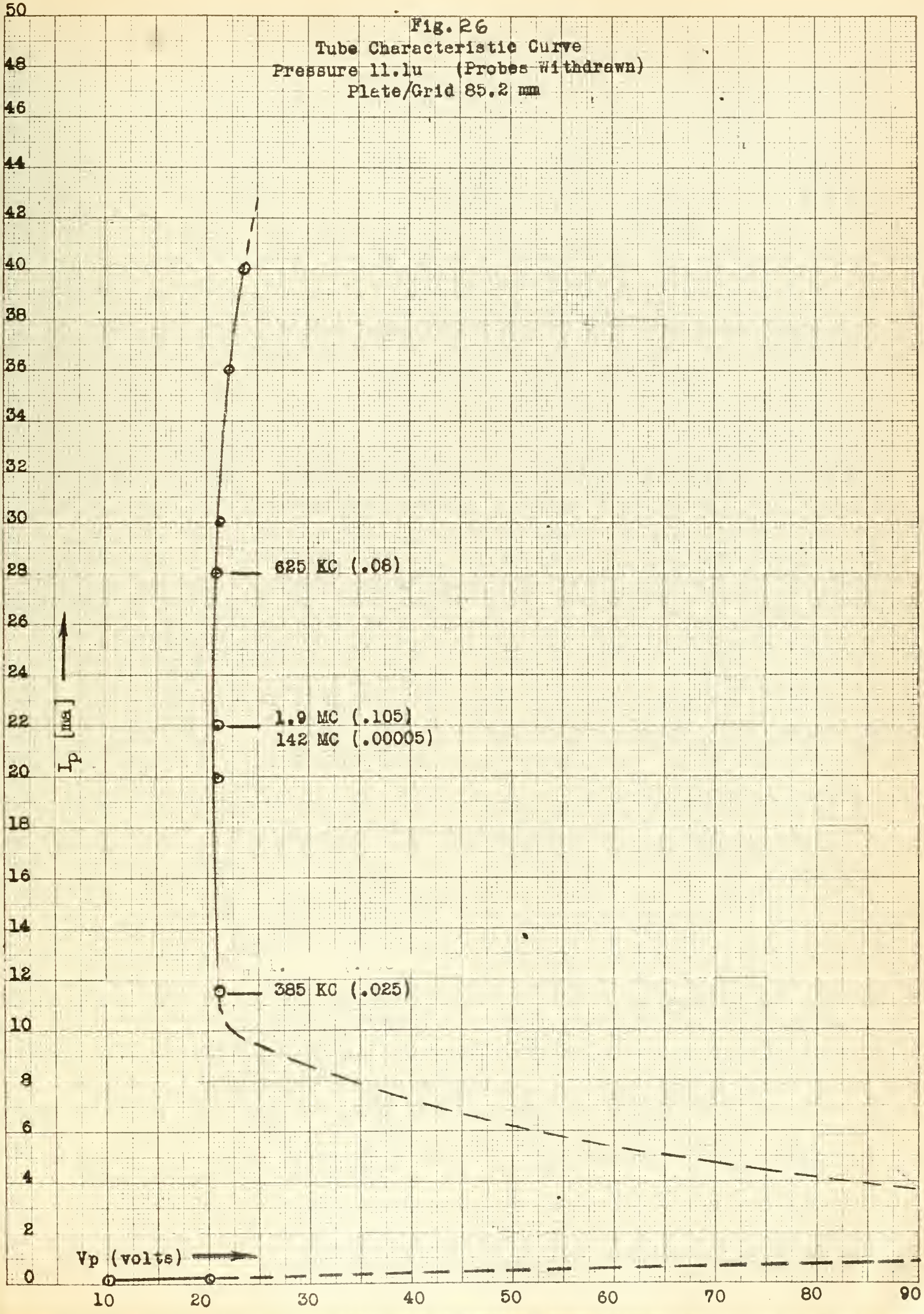


Fig. 26
Tube Characteristic Curve
Pressure 11.1u (Probes Withdrawn)
Plate/Grid 85.2 mm

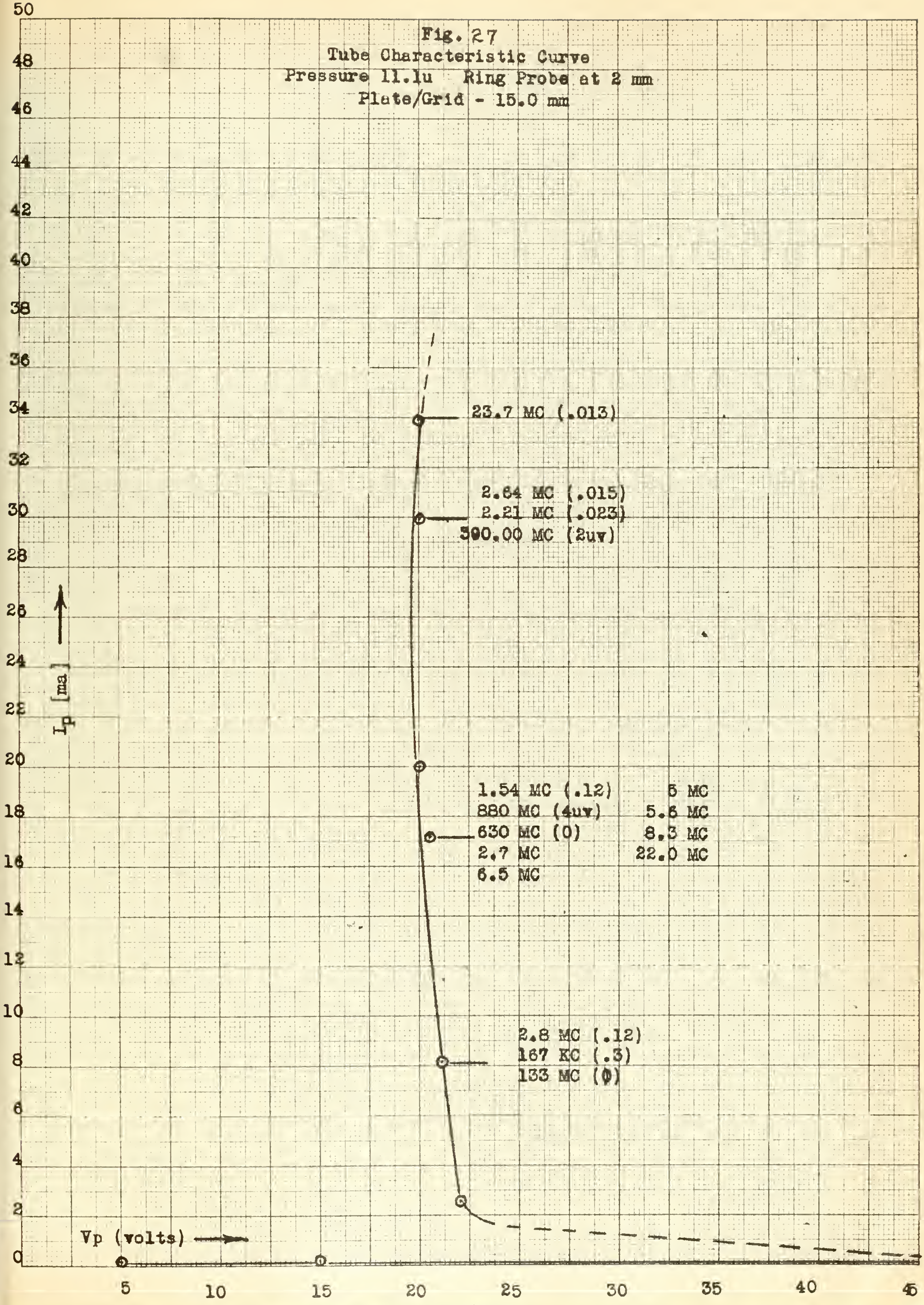


Fig. 27
Tube Characteristic Curve
Pressure 11.1u Ring Probe at 2 mm
Plate/Grid - 15.0 mm

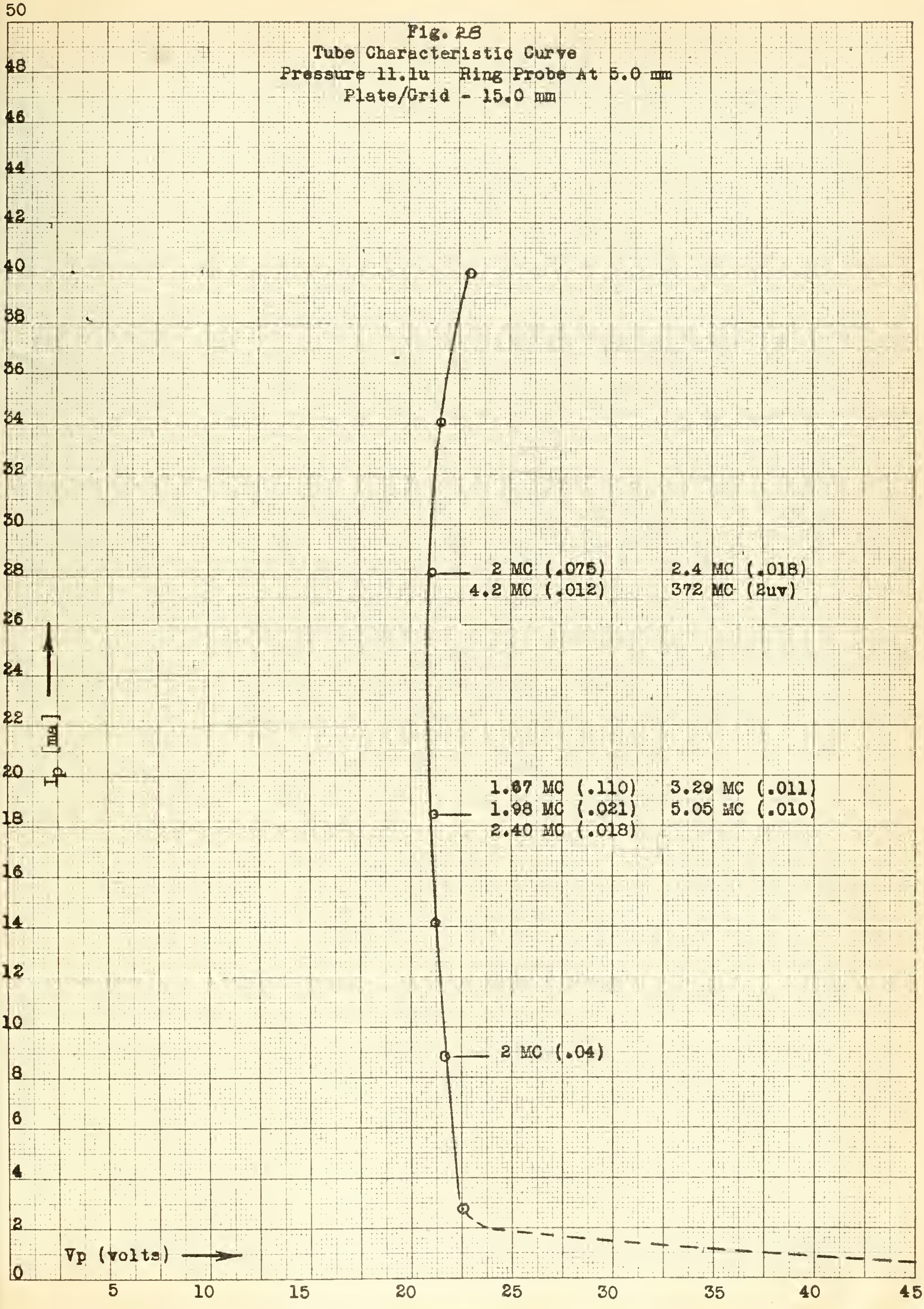


Fig. 28
Tube Characteristic Curve
Pressure 11.1u Ring Probe At 5.0 mm
Plate/Grid - 15.0 mm

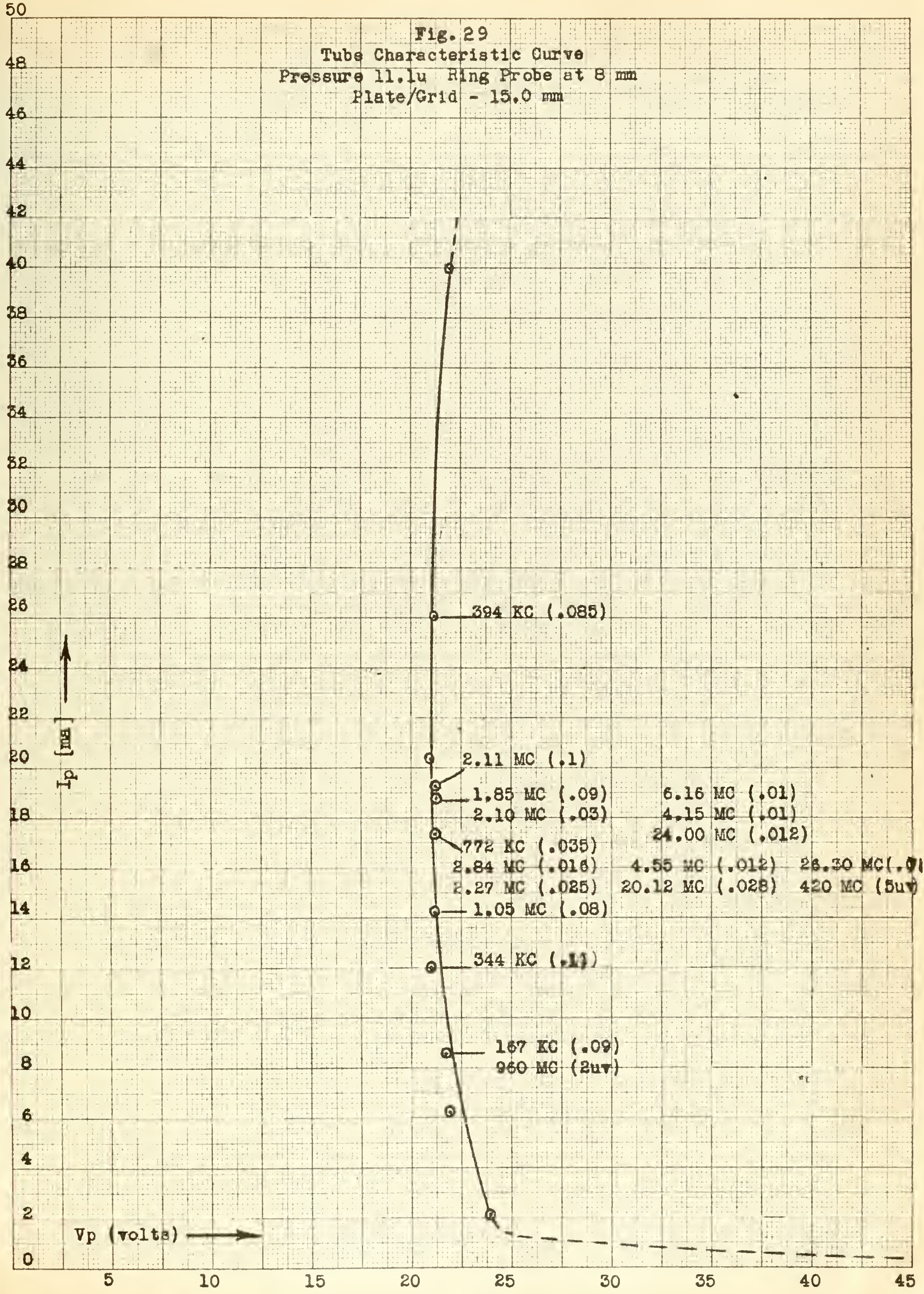


Fig. 29
Tube Characteristic Curve
Pressure 11.1u Ring Probe at 8 mm
Plate/Grid - 15.0 mm

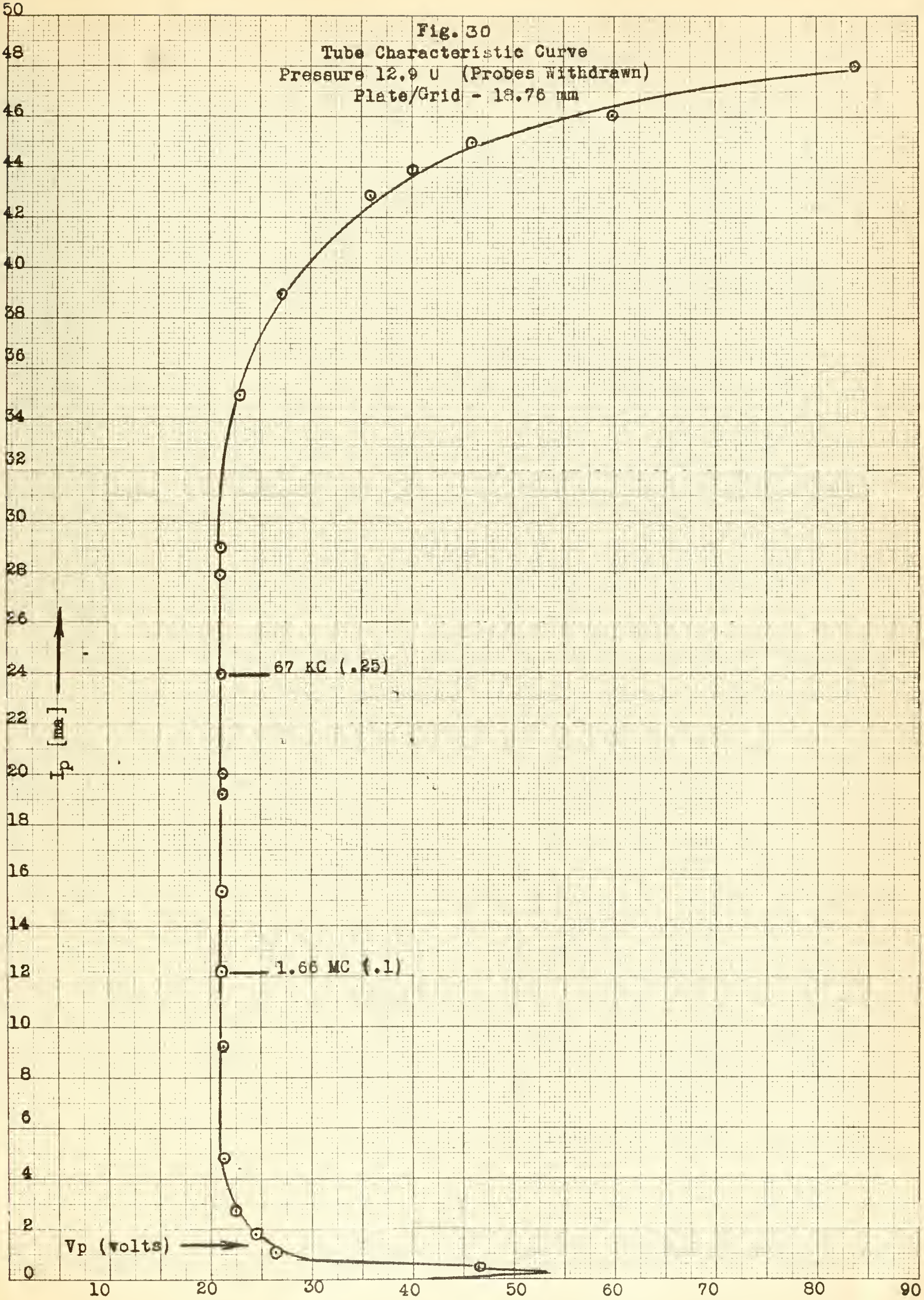


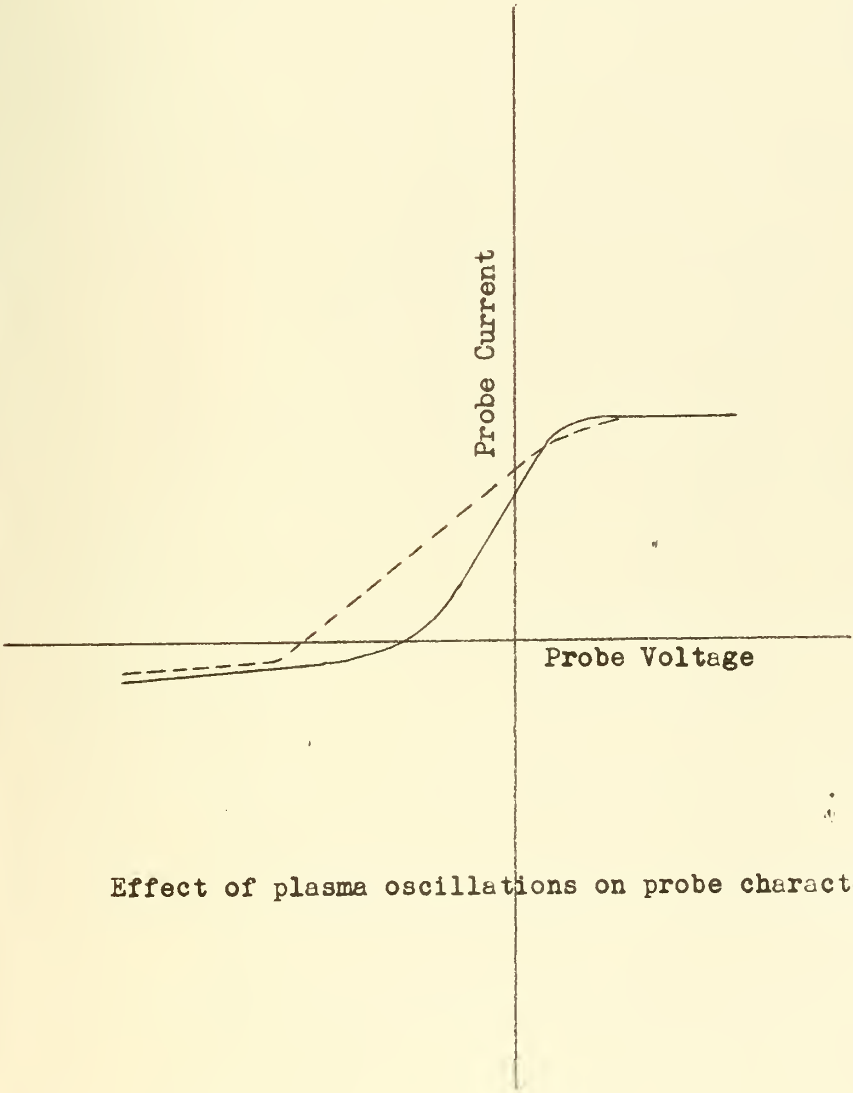
Fig. 30
Tube Characteristic Curve
Pressure 12.9 U (Probes Withdrawn)
Plate/Grid - 18.76 mm

PRESSURE [μ]	PROBE / GRID DISTANCE [MM]	V_p [VOLTS]	I_p [MA]	PLASMA POTENTIAL REL. TO ANODE. [VOLTS]	ELECTRON TEMP. [°K]	MAXIMUM ENERGY OF ELECTRONS. [VOLTS]	CALCULATED EL- ELECTRON OSC. FREQ. [MC]	OBSERVED ELECTRON OSC FREQ. [MC]	CALCULATED POSITIVE ION OSC. FREQ. [MC]	OBSERVED POSITIVE ION OSC FREQ. [KC]	FIG.
4.55	0.8	29	10.5	-25	51,800	34	4750	630, 680 722	1900	312	33
4.55	4.8	31	10.5	-30	7,200	31.5	163	370	600	95, 2000	33
4.55	7.7	32	10.5	-33	3,870	38	- - -	- - -	- - -	- - -	33
8.0	1.0	23	10.0	-21	30,500	30	203	665, 712	745	- - -	35
8.0	2.5	23	10.0	-21	30,500	30	203	500, 640	745	1250	35
8.0	4.8	23	10.0	-21	30,500	30	203	631, 668 720	745	384	35
8.0	8.2	23	10.0	-21	30,500	30	203	635, 680 722, 760	745	1430	35

SUMMARY OF PROBE ANALYSIS

FIG. 31

Fig. 32



Effect of plasma oscillations on probe characteristic

Fig. 33

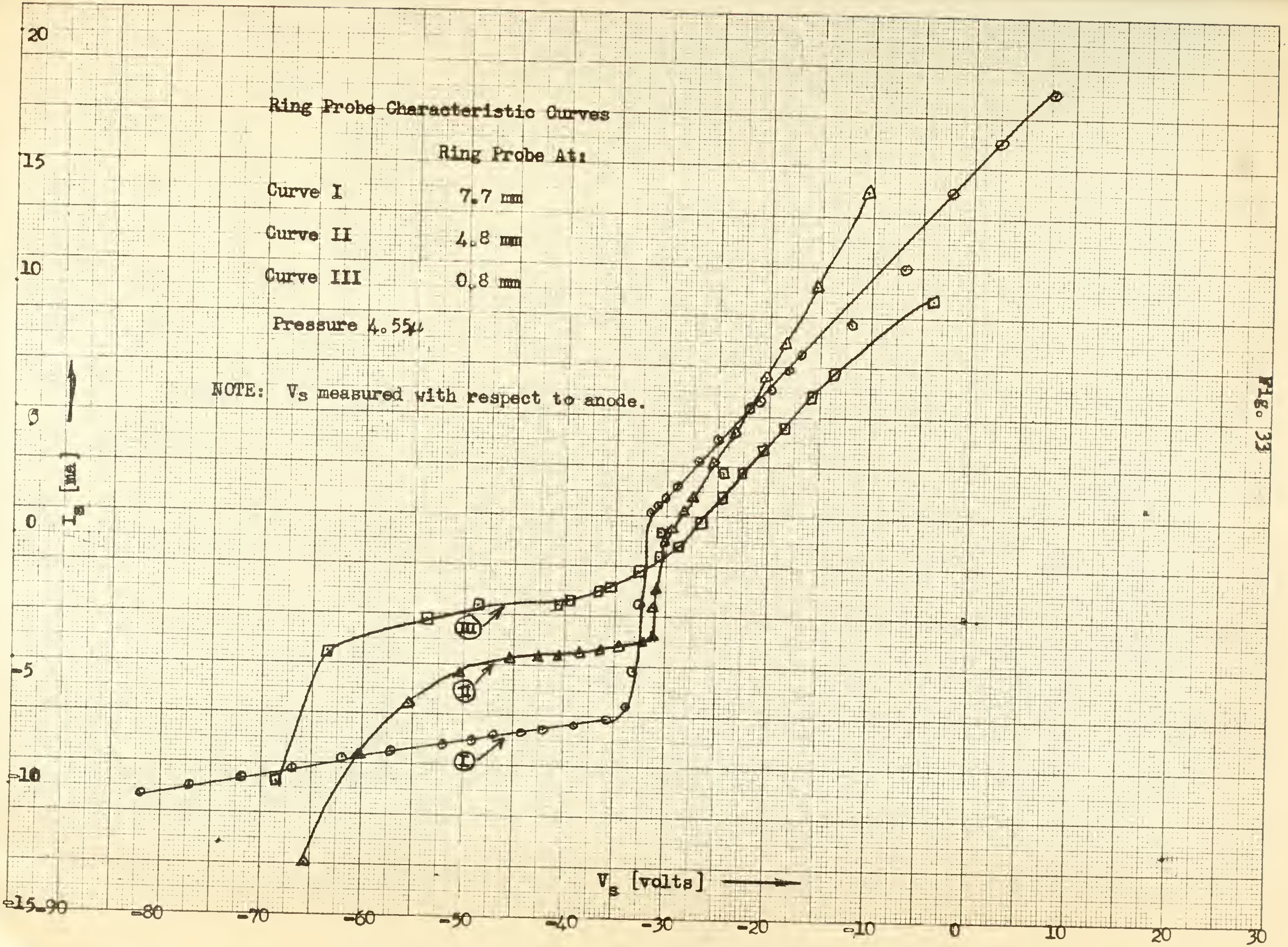

Ring Probe Characteristic Curves
Ring Probe At:
Curve I 7.7 mm
Curve II 4.8 mm
Curve III 0.8 mm
Pressure 4.55μ
NOTE: V_s measured with respect to anode.
I
II
III
I_s [ma]
V_s [volts]
20
15
10
5
0
-5
-10
-15
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30

Fig. 34

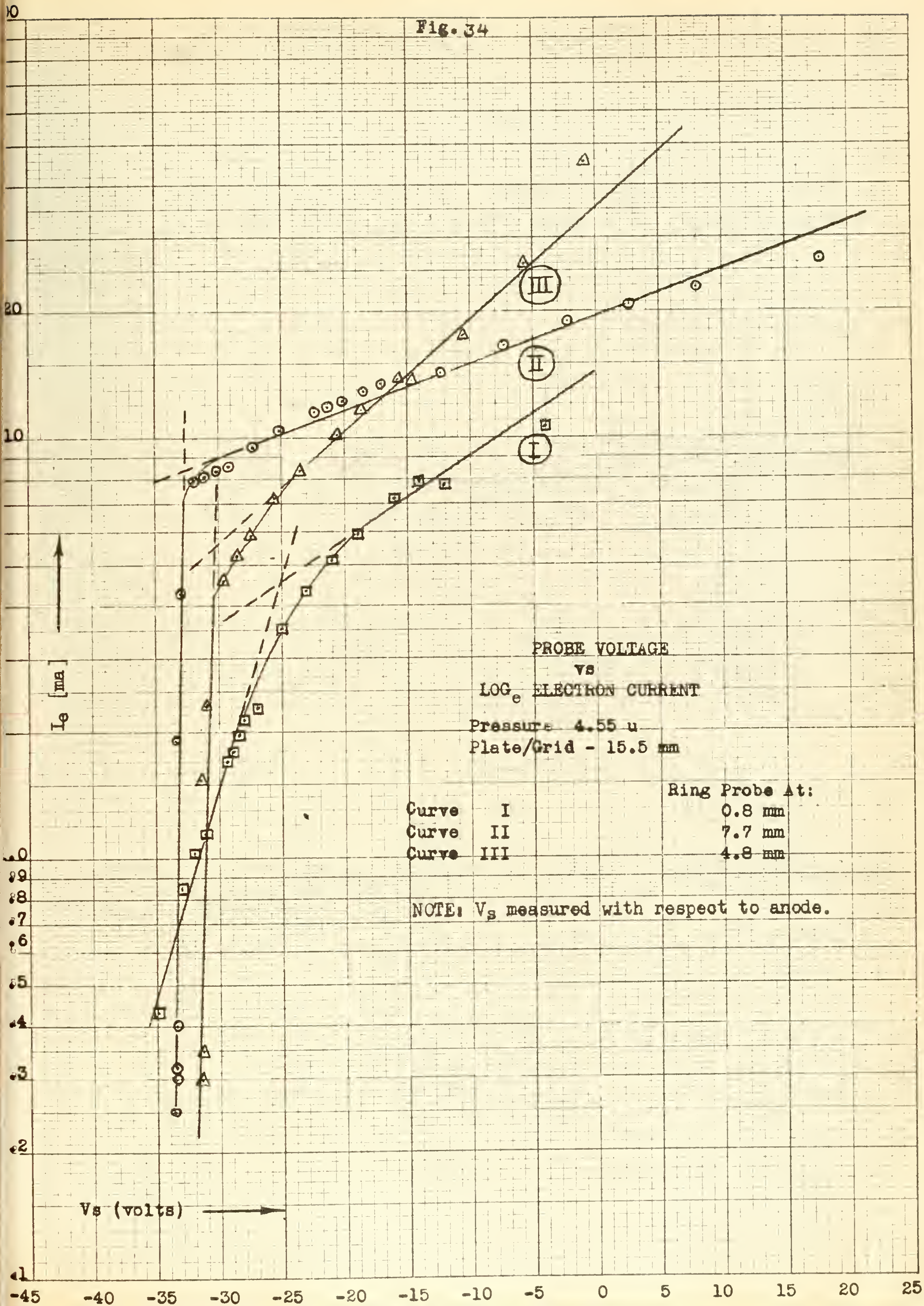
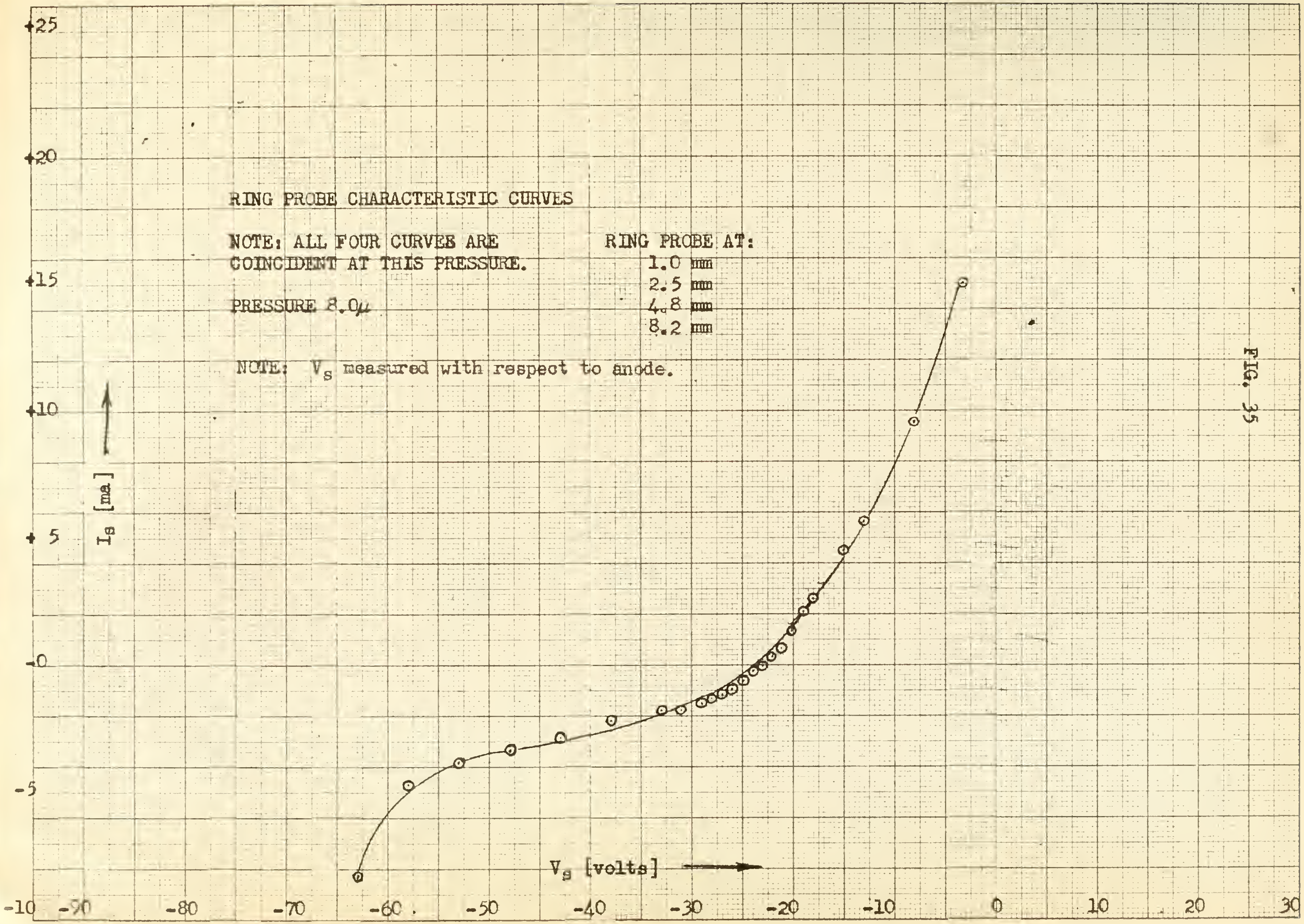

PROBE VOLTAGE
vs
LOG_e ELECTRON CURRENT
Pressure 4.55 u
Plate/Grid - 15.5 mm
Ring Probe At:
Curve I 0.8 mm
Curve II 7.7 mm
Curve III 4.8 mm
NOTE: V_s measured with respect to anode.
III
II
I
I_e [ma]
Vs (volts)
20
10
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25

FIG. 35



RING PROBE CHARACTERISTIC CURVES

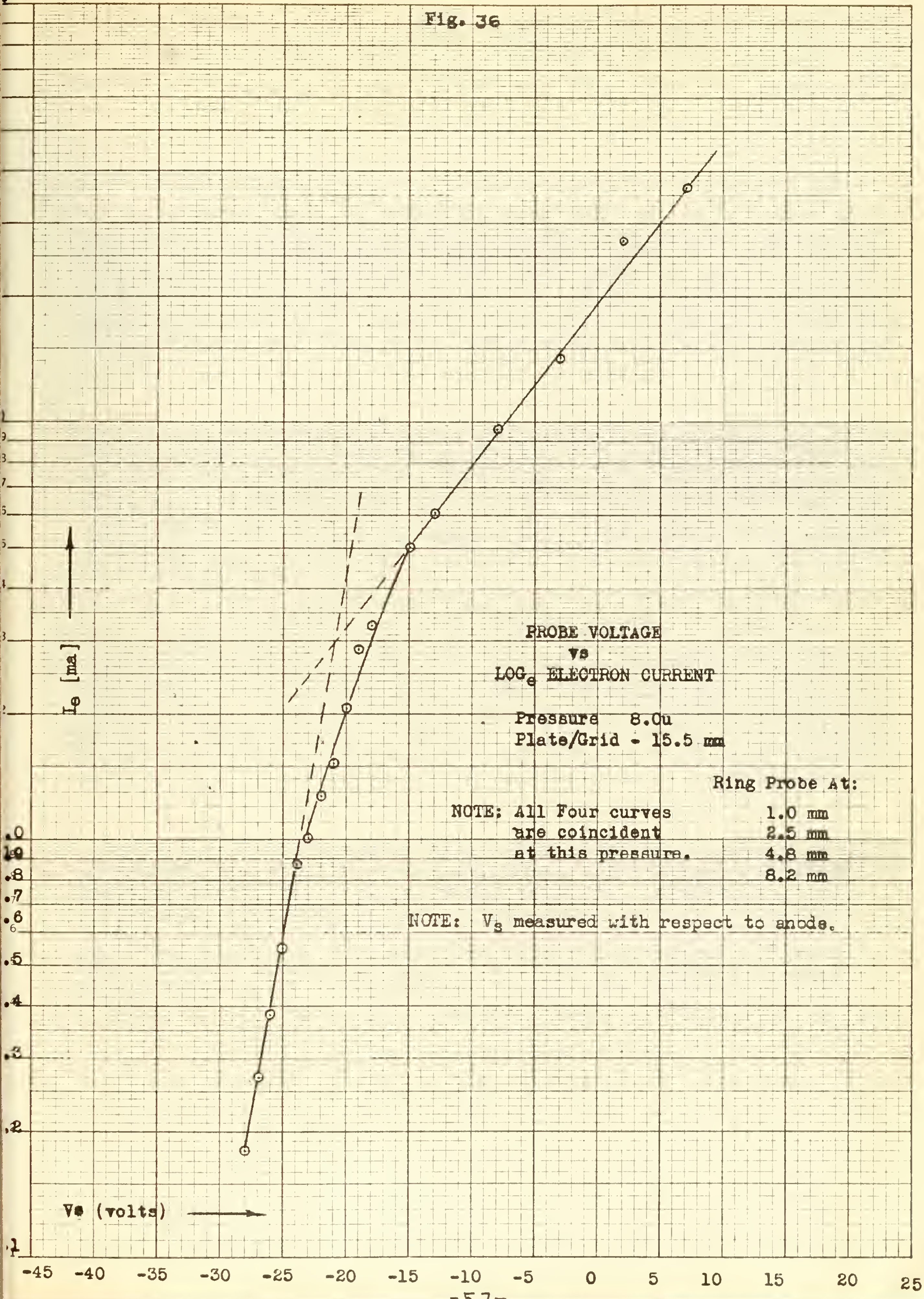
NOTE: ALL FOUR CURVES ARE COINCIDENT AT THIS PRESSURE.

PRESSURE 8.0μ

RING PROBE AT:
1.0 mm
2.5 mm
4.8 mm
8.2 mm

NOTE: V_s measured with respect to anode.

Fig. 36



PROBE VOLTAGE
vs
LOG_e ELECTRON CURRENT

Pressure 8.0u
Plate/Grid - 15.5 mm

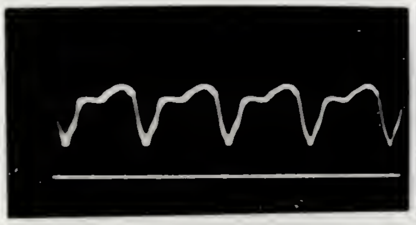
Ring Probe At:

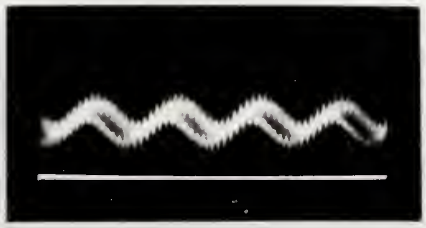
NOTE: All Four curves are coincident at this pressure.

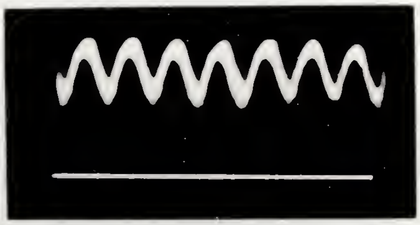
1.0 mm
2.5 mm
4.8 mm
8.2 mm

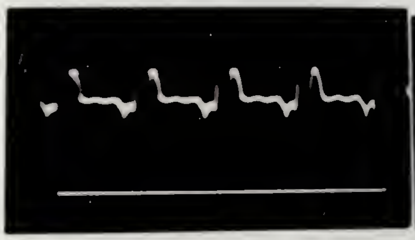
NOTE: V_s measured with respect to anode.

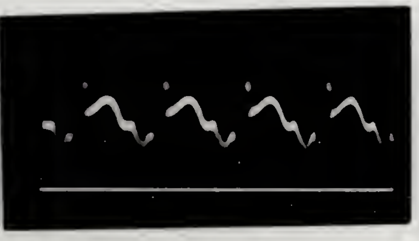
Fig. 37

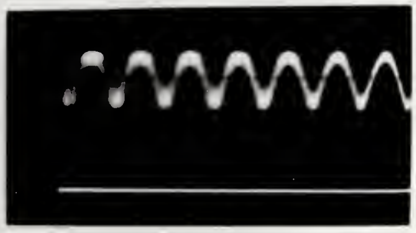

57 KC (0.4) Fig. 17

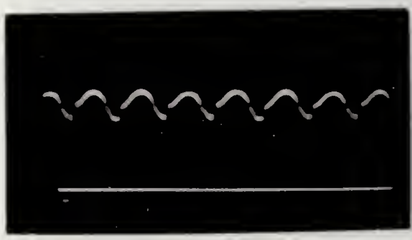

83.3 KC (0.1[illegible]) Fig. 17

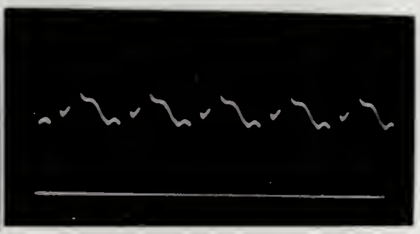

1.25 MC (0.[illegible]) Fig. 17

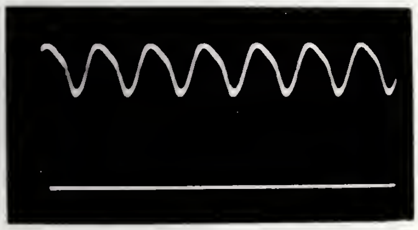

19.25 KC (1.3) Fig. 17

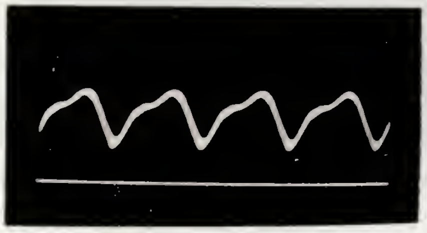

40 KC (0.16) Fig. 18

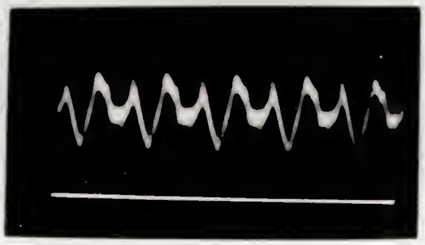

1.4 MC (0.[illegible]) Fig. 18

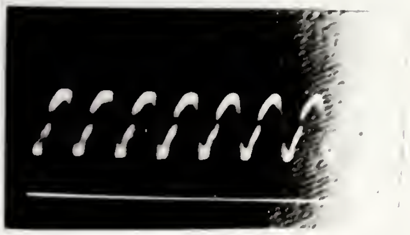

134 KC (0.39) Fig. 18


95 KC (0.125) Fig. 18


61.5 KC (0.99 Fig. [illegible]

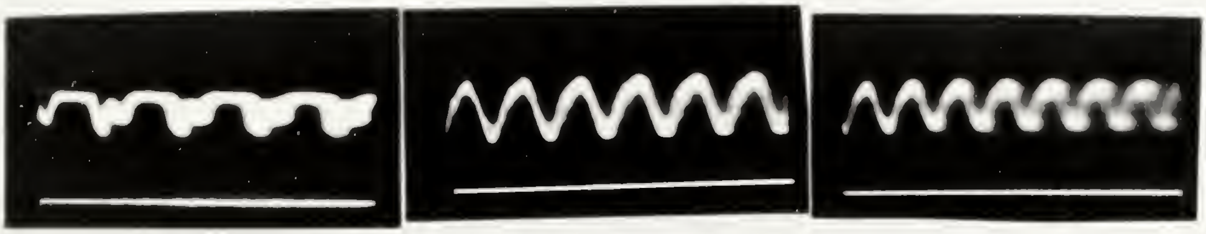

[illegible] KC ([illegible]) Fig. 17


1 MC (0.17) Fig. 18

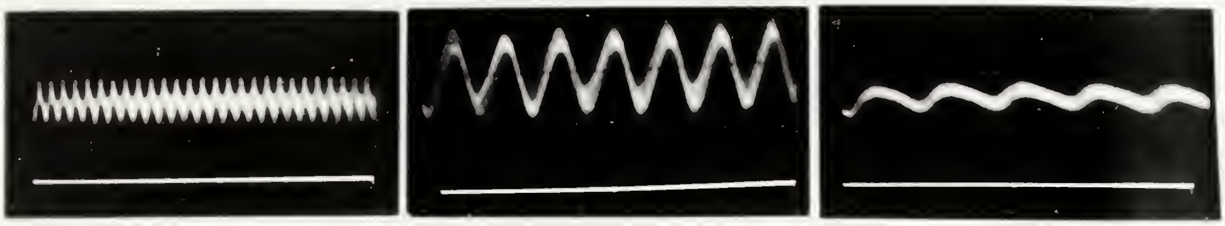

13.[illegible] KC ([illegible]) Fig. 17

TYPICAL LOW FREQUENCY OSCILLATIONS

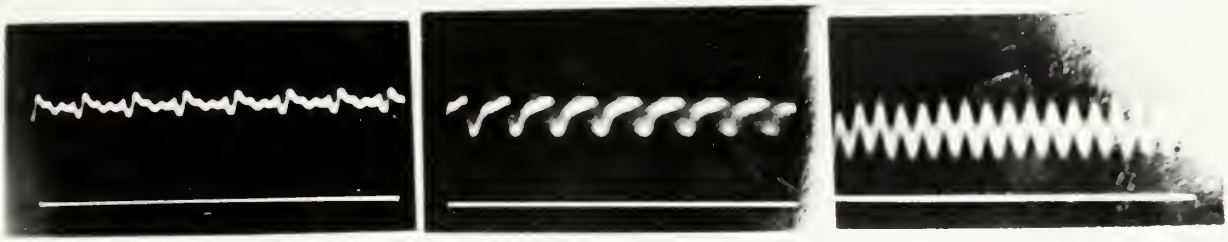
Fig. 38



[illegible] KC (0.03[illegible]) Fig. [illegible] 1.54 MC (0.2[illegible]) Fig. [illegible] 1.[illegible] MC (0.0[illegible]) F[illegible]



1.[illegible] MC (0.19) Fig. [illegible] 1.43 MC (0.[illegible]) Fig. 2[illegible] 410 KC (0.[illegible]) F[illegible]



[illegible] KC (0.1[illegible]) Fig. [illegible] [illegible] KC (0.[illegible]) Fig. [illegible] [illegible]

TYPICAL [illegible] FREQUENCY OSCILLATIONS

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